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Estimation and recovery of industrial low-grade waste heat in Belgium

Perspectives of Carnot Batteries

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Abstract

In the pursuit of sustainable energy transition, enhancing energy efficiency stands as a pivotal strategy to mitigate global energy consumption. A significant portion of primary energy is however lost as waste heat during various energy conversion processes, with a notable amount emitted at low temperatures. This paper examines the possibilities of waste heat recovery, with a specific focus on low-temperature waste heat recovery, emphasizing the thermodynamic constraints and technological solutions for its utilization.

The study explores the emerging Carnot Battery technology as a scalable and cost-effective energy storage solution for recovering low-temperature waste heat. With Belgium as a case study, where energy consumption remains substantial across industrial sectors, this analysis quantifies and characterizes the waste heat potential, particularly focusing on low-temperature waste heat, to provide insights into its recovery and utilization.

Through a comprehensive examination of waste heat recovery technologies, including Heat Pumps, Organic Rankine Cycles, and Carnot Batteries, this thesis aims to provide an overview of the potential benefits of waste heat recovery on a global industrial scale in Belgium.

Acknowledgements

I would like to extend my deepest gratitude to my friends for their continuous encouragement, support, and all the moments spent discussing our topics. Your unwavering support has been a source of strength and inspiration throughout this whole year.

To my advisor, Antoine, thank you for your invaluable guidance and kindness throughout this thesis.

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Contents

List of acronyms

AFF	Avoided Fossil Fuel
AHP	Absorption Heat Pump
C	Construction sector
COP	Coefficient of Performance
C&P	Chemical and Petrochemical sector
CDE	Carbon Dioxide Emissions
EF	Emission Factor
EI	Energy Intensity
FEC	Final Energy Consumption
FFU	Fossil Fuel Usage
F&T	Food and Tobacco sector
HC	Heat Coverage
HE	Heat Engine
HP	Heat Pump
HT	High Temperature (above 300°C)
HTHP	High Temperature Heat Pump
I&S	Iron and Steel sector
IWH	Industrial Waste Heat
LT	Low Temperature (below 100°C)
M	Machinery sector
M&Q	Mining and Quarrying sector
LAES	Liquid Air Energy Storage
LT	Medium Temperature (between 100 and 300°C)
LTES	Latent Thermal Energy Storage
NFM	Non-Ferrous Metals sector

NMM	Non-Metallic Minerals sector
NS	Non-Specified sector
ORC	Organic Rankine Cycle
PCE	Polynomial Chaos Expansion
PCM	Phase Change Material
PEF	Primary Energy Factor
PPP	Paper, Pulp and Print sector
PTES	Pumped Thermal Energy Storage
RTE	Round Trip Efficiency
STES	Sensible Thermal Energy Storage
TE	Transport equipment sector
TES	Thermal Energy Storage
TI-PTES	Thermally Integrated Pumped Thermal Energy Storage
T&L	Textile and Leather sector
VCHP	Vapour Compression Heat Pump
WH	Waste Heat
WHF	Waste Heat Factor
W&WP	Wood and Wood Products sector

1

Introduction

IN the realm of energy transition towards sustainability, boosting energy efficiency emerges as a critical strategy for cutting global energy consumption. However, energy conversion processes exhibit significant losses, with 72% of primary energy being lost [1]. Yet, within this challenge lies an opportunity—an untapped reservoir of potential awaiting discovery on a global scale.

1.1 Global waste heat recovery potential

More than half of primary energy consumption is being dissipated as waste heat, however, it does not represent its true potential. Thermodynamically, it is indeed impossible to achieve complete conversion of heat into useful work, and the efficiency potential of conversion diminishes with temperature. In their analysis on global water heat potential, Forman et al. [1] emphasized that 63% of this waste heat is generated at low temperatures, below 100°C, therefore significantly limiting its recoverability. They identified the Industrial and Transportation sectors as holding the most promise for low-temperature waste heat recovery, as depicted in Figure 1.1.

1.2 Technological recovery of waste heat

When considering waste heat potential, one might envision technologies that convert it into a more valuable form of energy, such as higher-temperature heat or electricity. Many technological solutions are already being studied and implemented globally, with heat pumps and Organic Rankine Cycles being among the most investigated examples. Industrial waste heat recovery stands out as the most thoroughly investigated sector due to its abundant waste heat potential. While the transportation sector also

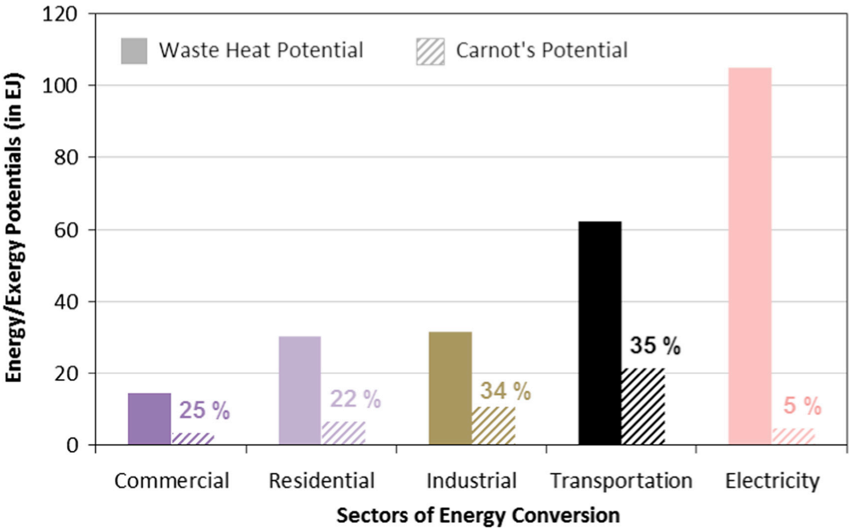


Figure 1.1 Sectoral waste heat and Carnot's potential [1]. Carnot potential of waste heat expresses the maximum retrievable technical work, Industry and Transportation being the most promising sectors in this matter.

shows promise, practical constraints make it less suitable for the implementation of recovery technologies, primarily due to the challenges associated with the size of such technologies.

But as renewable energy penetration into our energy systems continues to grow, so do the energy storage needs. In this context, an emerging electrical storage technology could emerge as a relevant alternative for low-temperature waste heat recovery: the Carnot Battery. By utilizing waste heat as a heat source, it provides a scalable, cost-effective, and location-independent alternative to existing storage technologies such as Pumped Hydro Energy Storage or Compressed Air Energy Storage. This technology is still in its early stages of development, but its study is increasing, under various localized applications. However, its integration potential on a global scale remains largely unexplored.

1.3 Application to the Belgium case

With a population exceeding 11 million, Belgium experiences substantial energy consumption driven by a combination of industrial, commercial, and residential demands. While nuclear power plays a significant role in electricity generation, fossil fuels such as natural gas remain essential for fulfilling energy requirements across various sectors such as Chemical, Food, Non-metallic minerals, and Iron and steel industries.

Despite endeavors to transition towards cleaner energy sources, Belgium continues to face challenges in reducing its carbon footprint and achieving climate objectives, notably due to limited renewable energy potential. Consequently, there is a growing emphasis on exploring innovative solutions for enhancing energy efficiency and recovering waste heat to optimize energy utilization and alleviate environmental impact.

In this context, the objective of this thesis is to explore and characterize the waste heat potential of the Belgian industry, with a specific focus on its low-temperature segment, and to examine its recovery potential. The analysis will begin with an overview of waste heat and the methods used for its estimation. Subsequently, it will delve into the quantification and characterization of the industrial waste heat potential. The analysis will then explore the possibilities for recovering low-temperature waste heat, providing insights into their technological aspects. Furthermore, the assessment will include an evaluation of the potential of Carnot Batteries in recovering the previously identified waste heat, alongside the potential of integrating Heat Pumps and Organic Rankine Cycles.

Ultimately, this analysis aims to provide guidelines for the recovery of waste heat and to quantify the corresponding benefits it could bring on a global scale.

2

Waste heat estimation - a literature review

ESTIMATING industrial waste heat potential involves a range of methods, each with its inherent uncertainties. This chapter examines various approaches to estimating waste heat potential within the Belgian industry, highlighting the most promising methodologies in the frame of this analysis.

2.1 Definition of Industrial Waste Heat and its Potential

When exploring the methodological possibilities to assess the waste heat potential, it is fundamental to start by defining the concept of waste heat and clarifying the potential that can be assessed.

2.1.1 Waste heat definition

In their categorization and literature review on waste heat estimation methods, Brueckner et al. [2] defined waste heat as "all forms of heat (latent as well as sensible) that escape a system and are not the intended purpose of the system", excluding therefore heat generated from combined heat and power generation. Waste heat can be released through thermal carriers, convection or radiation at a surface. This analysis, like the majority in the literature, will not consider this latter diffusively occurring waste heat due to the complexity of its recovery.

Waste heat carriers can vary widely, including liquids, gases, and solids, and can occur in numerous ways, such as exhaust gases from engines or furnaces, wastewater from washing, cooling air from turbomachinery, or even heat contained in newly manufactured commodities like hot steel.

2.1.2 Waste heat potential definition

The definition of waste heat being clearly established, it is essential to consider the type of potential to be assessed, which varies based on the constraints taken into account, as summarized in Figure 2.1.

The least restrictive assessment is the theoretical potential, which considers only physical constraints, such as waste heat being above ambient temperature or contained within a medium carrier. The technical potential, on the other hand, evaluates the capability of recovery technologies to extract heat from its carrier, depending on specific operational conditions, such as minimum temperature requirements. This technical potential can be derived from theoretical technological data and generic process information or from practical considerations based on onsite plant data.

Lastly, the feasible and economic potential considers financial factors, such as interest rates, energy prices, and payback periods, to assess the economic viability of waste heat recovery systems.

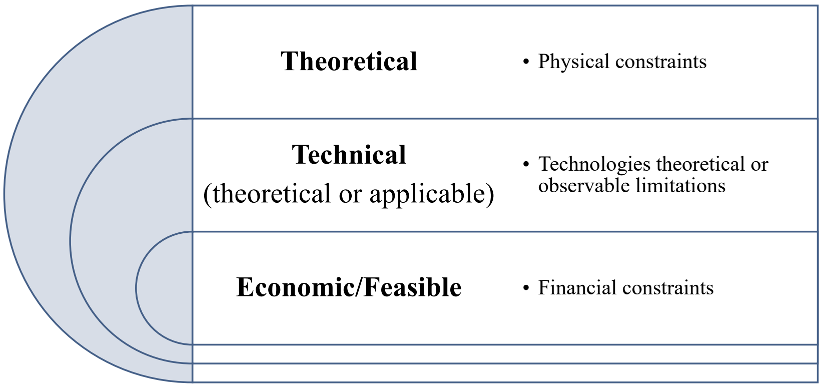


Figure 2.1 Waste heat potentials, reproduced from [2][3]

2.2 Waste heat estimation methods

The following section aims to review the waste heat estimation methods found in the literature.

2.2.1 Method classification

Waste heat characterization and estimation can be approached through various methodologies. Firstly, it is important to clarify the differences between bottom-up and top-down approaches. The first involves deriving general results from the aggregation of localized and specific data. For instance, it can entail calculating and combining the waste heat generated by individual processes within a plant. The bottom-up approach, on the other hand, involves drawing specific conclusions from general data and principles. For example, one might relate the waste heat of an industrial sector to its overall heat demand or productivity, then infer the waste heat production of a specific plant based on its production or energy demand.

The scale of the research significantly influences the selection of either the bottom-up or top-down approach. Indeed, the bottom-up method becomes increasingly complex and time-consuming for larger scales.

Figure 2.2 shows the methods classification provided by Brueckner et al. [2]. They acknowledge that categorizing a method is not always straightforward, as many methods employ a mixed approach to leverage the respective advantages of different techniques.

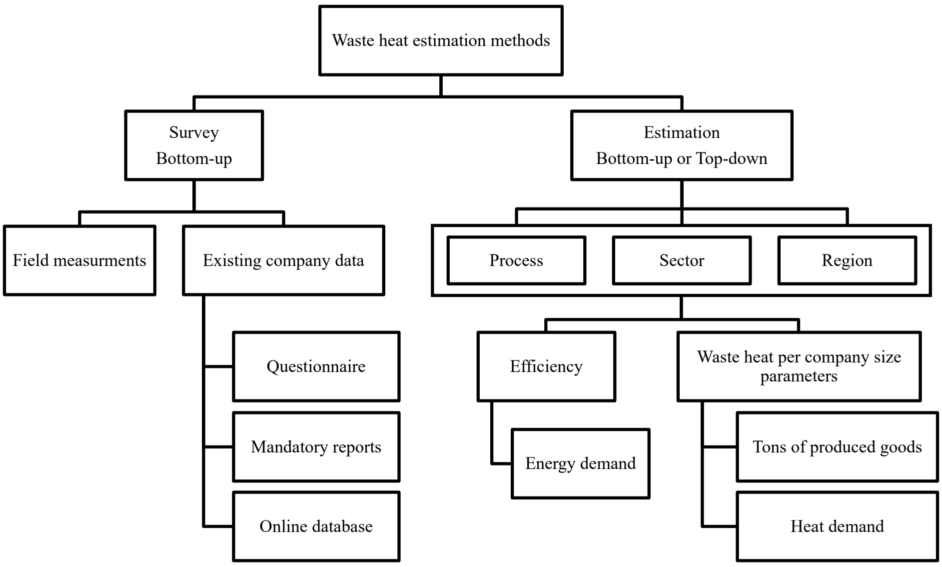


Figure 2.2 Classification of waste heat estimation methods, reproduced from [2]

The initial categorization of waste heat characterization methods hinges on whether results are derived from collected data or estimates. In the case of data collection, surveys can be conducted through field measurements or by gathering information from companies within the sector or region being investigated. This information can come from questionnaires, reports, or online databases. Regarding the on-site measurements, it is important to note that they can pose challenges due to the potentially high temperatures involved, which create difficult conditions for sensor operation.

On the other hand, estimation methods are applied on a much wider range of scales, encompassing a process, sector, country, or even an entire continent. The primary estimation techniques can involve relating waste heat generation to company parameters, such as size and productivity, or calculating waste heat as process losses based on efficiency metrics.

2.2.2 Waste heat calculation methods

Among the methods encountered in the literature, three could have been employed to estimate the waste heat potential of the Belgian industry. They are based on three methodological principles, described here-after.

Process losses

This methods consists of the evaluation of waste heat as a process loss, with the help of its corresponding efficiency. This way, in their estimation of the global waste heat potential, Forman et al. [1] assessed the cumulative waste heat potential for each subsector within the European Union: industrial, commercial, residential, transportation and electricity generation.

They developed a comprehensive database that compiles waste heat balance factors η_{EL}, defined as exhaust and effluent loss balance factors, for processes across various sectors including transportation, industry, residential, commercial, and electricity generation. Those balance factors are defined as the ratio of the stream energy output of process j (in this case the exhaust and effluent streams) to the energy product i input of the process, see Equation 2.1. To derive the waste heat Q_{WH} occurring in these conditions, it only requires to know the energy consumption E_{ij} of process j of a certain energy product i.

Waste heat as the heat streams energy content

$$\eta_{ij,EL} = \frac{\text{Exhaust and effluent energy output of the process } j}{\text{Energy product } i \text{ input of the process}} \tag{2.1}$$

$$Q_{WH} = \sum_{i}^{N} \sum_{j}^{M} E_{ij} \eta_{ij,EL} \tag{2.2}$$

This method embodies a bottom-up approach by aggregating the waste heat potential of individual processes within each sector to derive the overall waste heat potential. However, the energy balance factors applied in this calculation are sourced from existing research and adapted to the specific case under study. Thus, this method also exhibits characteristics of a top-down approach.

Exhaust gases energy content

Waste heat can also be assessed on the basis of the energy content of the process exhaust heat streams, which can be computed as in Equation 2.3. This formulation is however limited to the expression of the energy content of exhaust gases.

Waste heat as the heat streams energy content

$$Q_{WH} = \dot{V}\rho_{gas}C_{p,gas}\left(T_{gas} - T_0\right) \tag{2.3}$$

This bottom-up approach aims to quantify the waste heat potential of a sector by summing the exhaust streams of processes from all companies within that sector. The reference temperature T_0 represents the minimal discharge temperature of heat fluxes. This method requires specific information about the volume flow rate $\dot{V}$, as well as the stream's specific heat capacity C_p and density ρ. Brueckner et al. employed this approach to assess the industrial waste heat potential in Germany [4].

Such a methodology is particularly suitable for survey-based methods, as it relies on detailed process-specific data from individual companies, but only accounts for the waste heat related to the exhaust gases.

Extrapolation based on Waste Heat Factor

Another methodology for estimating waste heat potential involves correlating it with parameters characterizing companies or plants within a specific sector or region. Papapetrou et al. [5] employed this approach in a 2018 study, extrapolating waste heat potential at the European level using data from the UK for the years 2000-2003.

The calculations of this method are summarized in Equations 2.4 and 2.5. It hinges on the Waste Heat Factor (WHF), defined as the ratio of waste heat potential to heat consumption linked to the utilization of an energy product i for a given sector s in a reference country $refC$ and reference year 0. To update this factor for the considered year y and region, adjustments based on the Energy Intensity (EI) of both regions are necessary.

The sector-specific waste heat potential for the target region is then calculated by multiplying the updated Waste Heat Factors by the corresponding heat consumption linked to their respective energy products and summing the results.

Waste heat extrapolation

$$WHF^{s}_{i,BE} = (WHF_{refC,i})^{s}_{0}\frac{(EI^{s}_{BE})_{y}}{(EI^{s}_{refC})_{0}} \tag{2.4}$$

$$\Rightarrow Q_{WH} = \sum_{i}^{N} Q_{i} WHF^{s}_{i,BE} \tag{2.5}$$

2.2.3 Waste heat Carnot potential

The different waste heat potentials have been detailed here above, however, one must consider that quantifying the energy content of the waste heat does not express its potential to be turned into technical work. Referring to the second law of thermodynamics, it is understood that even under ideal conditions, only a fraction of the input heat can be converted into useful work, with the remainder dissipating to the environment.

In the realm of thermodynamics, the Carnot cycle serves as the benchmark for heat engine efficiency, illustrating the theoretical maximum efficiency achievable between two distinct temperature levels. When analyzing waste heat, the Carnot efficiency factor (η_C) provides insight into the maximum work output attainable from such sources, which is defined by their temperatures.

Applying this concept to the evaluation of waste heat enables a more precise assessment of the technical work that can be extracted. This measure, referred to as the Carnot Waste Heat potential (W^{C}_{WH}), delineates the upper limit of usable energy from this thermal resource and is expressed in Equation 2.6.

Carnot potential of waste heat

$$Q^{C}_{WH} = Q_{WH}\eta_{C} \quad \text{with} \quad \eta_{C} = \left(1 - \frac{T_{amb}}{T_{h}}\right) \tag{2.6}$$

3

Estimation of the Industrial Waste heat potential of Belgium

METHODOLOGICAL possibilities to quantify waste heat have been explored. The following chapter aims to outline the methodology chosen to derive the waste heat potential of the Belgian industry, and to present the resulting findings.

3.1 Scope of the analysis

This analysis aims to quantify the waste heat potential of the Belgian industry for the year 2022, the most recent year for which national energy consumption data was available at the commencement of this research, in October 2023.

3.1.1 Industrial sectors

A precise delineation of the sectoral scope is crucial for this analysis. Following the sectoral segmentation established by Forman et al. [1], a similar categorization has been adopted. Table 3.1 provides a summary of the industrial sectors included in this study, along with their corresponding acronyms, descriptions, and NACE classifications [6]. The acronyms introduced in this Table will be widely employed in the analysis.

Industrial sector	Acronym	NACE	Description
Iron and Steel	I&S	C.241	Manufacture of basic iron and steel, and of ferro-alloys
		C.2451	Casting of iron
Chemical and Petrochemical	C&P	C.20	Manufacture of chemicals and chemical products
		C.21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
Non-ferrous metals	NFM	C.244	Manufacture of basic precious and other non-ferrous metals
		C.2453	Casting of light metals
		C.2454	Casting of other non-ferrous metals
Non-metallic minerals	NMM	C.23	Manufacture of other non-metallic mineral products
Transport equipment	TE	C.29	Manufacture of motor vehicles, trailers and semi-trailers
		C.30	Manufacture of transport equipment
Machinery	M	C.28	Manufacture of machinery and equipment n.e.c.
Mining and Quarrying	M&Q	B.07	Mining of metal ores
		B.08	Other mining and quarrying
		B.099	Support activities for other mining and quarrying
Food and Tobacco	F&T	C.10	Manufacture of food products
		C.11	Manufacture of beverages
		C.12	Manufacture of tobacco products
Paper, pulp and print	PPP	C.17	Manufacture of paper and paper products
		C.18	Printing and reproduction of recorded media
Wood and wood products	W&WP	C.16	Manufacture of wood and products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
Construction	C	C.41	Construction of buildings
		C.42	Civil engineering
		C.43	Specialized construction activities
Textile and leather	T&L	C.13	Manufacture of textiles
		C.14	Manufacture of wearing apparel
		C.15	Manufacture of leather and related products
Non-specified (industry)	NS	C.22	Manufacture of rubber and plastic products
		C.31	Manufacture of furniture
		C.32	Other manufacturing

Table 3.1 Belgian industry sectoral segmentation, following NACE classification [6].

3.2 Methodology

Section 2.2.2 presented a review of the waste heat calculations method encountered in the literature, and transferable to our case of study. Table 3.2 summarizes the key considerations for each of the detailed methods, detailing the required input data, the approach and calculation method employed, and the associated accuracy.

Method	Process losses	Exhaust gas energy content	Waste heat factor extrapolation
Reference paper	Forman et al.[1] (2016) Bianchi et al. [3] (2019)	S. Brueckner et al. [4] (2017)	M. Papapetrou et al. [5] (2018)
Approach	Mixed	Bottom-up	Top-down
Transferable key figure	Process balance factor	-	Waste heat factor
Input data	Energy consumption	Exhaust gas nature and content	Heat consumption
Evaluated potential	Theoretical	Theoretical	Theoretical
Accuracy	Medium	Medium	Medium

Table 3.2 Literature review comparison of waste heat estimation methods adapted to the study of low-temperature industrial waste heat analysis.

3.2.1 Combination of bottom-up and top-down approaches

The primary objective of this analysis is to estimate the waste heat potential of the entire Belgian industry. Given the large scale of this undertaking, a bottom-up approach is deemed impractical. After excluding the "Exhaust gas energy content" method, the choice was narrowed down to the "Process losses" method and the "Waste heat factor extrapolation" method. Both have been applied at national scales and are known to provide a satisfactory level of characterization. However, each method relies on significant assumptions: the "Process losses" method assumes that the sector's activity can be broadly represented by aggregating several processes and their corresponding efficiencies. On the other hand, the "Waste heat factor extrapolation" method assumes that a sector's waste heat is primarily linked to its energy intensity and heat consumption and can be extrapolated from another period and region.

A notable advantage of the "Process losses" method is the detailed temperature data for exhaust and effluent streams provided by the comprehensive database compiled by Forman et al. [1]. This allows the characterization of waste heat temperatures, which is crucial given the temperature-dependent Carnot factor discussed previously, reflecting the quality of the heat and its retrievable technical work. This method thus enables a more detailed sectoral analysis while still providing general results.

Additionally, a survey was designed to collect localized data from Belgian companies, aiming to validate the results obtained through the database and refine the balance factors used. The survey included questions on the efficiency of industrial processes and data on exhaust and effluent streams, allowing for an auxiliary analysis based on the "Exhaust gas energy content method". The questionnaire, adapted from the existing Data Collection Survey of the European project *CE-HEAT* [7], can be found in Appendix A. In total, 124 companies across the 12 investigated sectors were contacted, but the responses were insufficient to draw any comprehensive conclusions.

3.2.2 Parameters

The methodology necessitates the utilization of two categories of parameters: process data derived from the Forman et al. database [1] and sectoral energy consumption data, characterized by their respective energy products.

Process Data

For each industrial sector, Forman et al. provide a detailed account of the process and utilization of energy products concerning the industrial sector, the specific energy product i, and the industrial process j. It is noteworthy that Forman et al. distinguished between exhaust and effluents in their study. They defined Exhaust in relation to exhaust or flue gases and vapor, while effluents were related to coolant streams, including air, water, or other mediums. Table 3.3 summarizes the utilized parameters.

Parameter	**Description**
Process energy consumption	
E_i	Energy consumption of a given energy product i
μ_{ij}	Share of the energy consumption of the energy product i engaged in process j
Process energy balance	
$\eta_{ES,ij}$	Energy balance factors linked to the energy services share of the process j energy output
$\eta_{EL,ij}$	Energy balance factors linked to the exhaust and effluent losses share of the process j energy output
$\eta_{OL,ij}$	Energy balance factors linked to other losses share of the process j energy output
Process waste heat characterization	
$\sigma_{ex,i}$	Share of waste heat linked to the energy source i and emitted as exhaust gases
$T_{ex,i}$	Temperature at which the related exhaust gases are released
$\sigma_{ef,i}$	Share of waste heat linked to the energy source i and emitted as effluent gases
$T_{ef,i}$	Temperature at which the related effluent gases are released

Table 3.3 Industrial processes database parameters

Sectoral energy consumptions

The collection and characterization of energy consumption per industrial sector and per energy product are fundamental to this study. These data were extracted from the Statbel database, which provides the Belgian global energy balance for the year 2022 [8].

3.2.3 Calculations

The computation of the waste heat potential of the Belgium Industry follows the scheme depicted in Figure 3.1.

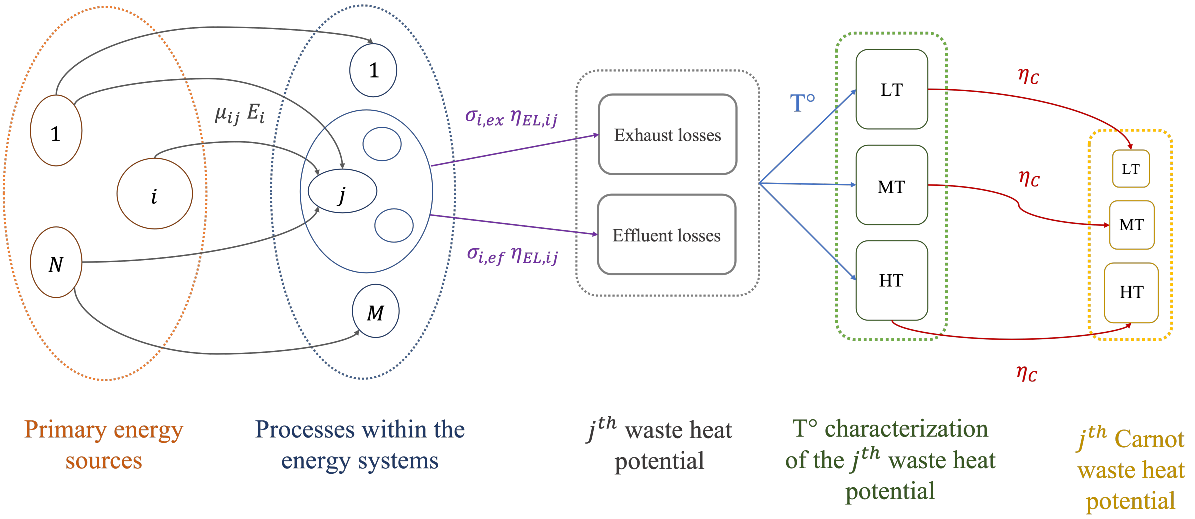


Figure 3.1 Waste heat potential calculation, based on [3].

The energy consumption of each sector is categorized according to its primary energy source i. For each energy consumption E_i, a fraction μ_{ij} is allocated to a process j. This latter is characterized by 3 energy balance factors η_{ES}, η_{EL} and η_{OL}, respectively related to the Energy Services, the Exhaust and Effluent Losses, and the Other Losses [1].

The Forman et al. database [1] provides data on the proportions $\sigma_{ex,i}$ and $\sigma_{ef,i}$ of waste heat generated as exhaust and effluent at the respective temperatures $T_{ex,i}$ and $T_{ef,i}$.

The characterization of waste heat temperatures is divided into three ranges: low temperature (below 100°C), medium temperature (100°C to 300°C), and high temperature (above 300°C). This temperature classification is common when characterizing waste heat temperatures [1][3].

To eventually assess the quality of this waste heat, meaning its potential to be converted into technical work, the Carnot Potential quality factor η_C is applied on each stream, depending on its temperature.

$$W_{WH}^{C} = Q_{WH}\eta_C = Q_{WH}\left(1 - \frac{T_{amb}}{T_{WH}}\right) \tag{3.1}$$

3.3 Database update

Before conducting the estimation of the industrial waste heat potential, attention should be drawn to the database at the basis of the methodology, and data refinement should be performed. The database developed by Forman et al. [1], and from which the balance factors are derived, is primarily based on 15 different sources. These sources themselves collected efficiencies and temperatures from various other references, making a comprehensive validation of the entire database challenging. To identify the parameters with the most significant impact on the global industrial waste heat Carnot potential, a sensitivity analysis was conducted using Polynomial Chaos Expansion (PCE) with the *rheia* package in Python [9]. This approach will facilitate further refinement of documentary data for these critical parameters.

3.3.1 Polynomial Chaos Expansion: a sensitivity analysis tool

Polynomial Chaos Expansion (PCE) is a powerful mathematical tool used to perform uncertainty quantification and sensitivity analysis on a certain model. It represents uncertain inputs as polynomial functions, and then express the model as a series in terms of these chosen polynomials functions. The coefficients c_i are determined with some regression or spectral projection. In the following, Y is the model output, c_i are the coefficients, Ψ_i are the polynomial basis functions, and ξ are the random variables.

$$Y = \sum_i c_i \Psi_i(\xi) \tag{3.2}$$

One can thus propagate the input uncertainties through the model thanks to their polynomial expressions, and obtain the distribution of the output.
The *rheia* package in Python facilitates this analysis, allowing the evaluation of models and providing access to the Sobol indices associated with each uncertain considered input. Such indices are used to quantify the sensitivity of a model output to uncertain inputs by describing the proportion of the total variance attributable to the uncertainty of each input parameter. The first-order Sobol indices, S_i, account for the effect of individual parameters, while the total Sobol indices, S_{T_i}, include both individual effects and the mixed influences of multiple parameters. In the following, V_i is the variance contribution from input i, V_{ij} is the contribution from the interaction between inputs i and j, and so on.

$$Var(Y) = \sum_{i=1}^{n} V_i + \sum_{0\leq i\leq j\leq n} V_{ij} + \ldots + V_{1,2,\ldots,n} \tag{3.3}$$

$$S_i = \frac{V_i}{Var(Y)} \tag{3.4}$$

$$S_{T_i} = \frac{V_i + \sum_{j \neq i}^{n} V_{ij} + \dots}{\mathrm{Var}(Y)} \tag{3.5}$$

$$= 1 - \sum_{j} S_j \qquad \text{where} \quad j \in \{(0, ..., n); j \neq i\} \tag{3.6}$$

3.3.2 Critical parameters

The aim is to apply this method to the previously detailed Industrial Waste Heat estimation model, in order to identify critical parameters from the Forman et al. database. To achieve this, an arbitrary relative variation of 10% was applied to each parameter, assuming they follow a uniform random distribution. The analysis focused on first-order Sobol indices due to the excessive computation time required for second-order indices calculations. It is important to note that this first-order analysis is not sufficient to capture the full conjunctive effects of the uncertainty of multiple parameters. Indeed, the variations associated to some parameters can combine since the Waste Heat Carnot potential can be expressed as:

$$W_{WH}^{C} = E_i \mu_{ij} \eta_{EL} \left(1 - \frac{T_{amb}}{T_{WH}}\right)$$

where E_i is the energy consumption of the energy product i, μ_{ij} is its fraction engaged in process j, η_{EL} is the exhaust and effluent losses balance factors, and T_{amb} is the ambient temperature.

Out of the 536 parameters analyzed, only 29 parameters were identified as significant, with Sobol indices above 1%, depicted on Figure 3.2.
The large majority of these parameters (28 out of 29), originates from two primary sources: the balance factors were primarily obtained from the paper of Cullen et al. "Theoretical Efficiency Limits for Energy Conversion Devices" [10] and the waste heat temperatures were extracted from the report "Waste Heat Recovery: Technology and Opportunities in the U.S." [11].

Cullen et al. initially sourced efficiency values from the 1996 paper "Regional and Global Exergy and Energy Efficiencies" [12], and updated them using efficiency enhancements between 1995 and 2005 provided by the 2008 IEA report "Worldwide Trends in Energy Use and Efficiency: Key Insights from IEA Indicator Analysis" [13].

A similar approach was therefore adopted to update the database, wherein efficiencies were adjusted to accommodate the energy intensity enhancements in Belgium since 2005, sourced from the International Energy Agency [14]. It was assumed that these improvements influence in the same proportion both effluents and exhaust losses.

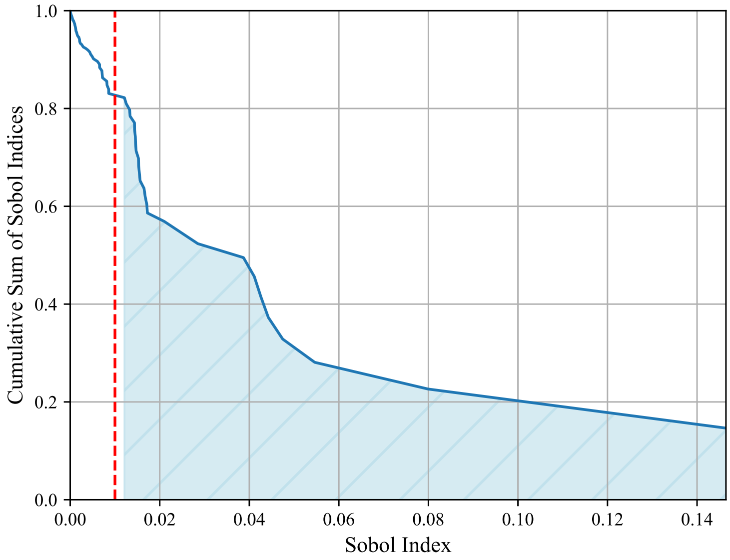


Figure 3.2 Cumulated Sobol indices. The blue hashed region represents the 29 most influencing parameters out of 536.

3.4 Results

The following section presents the outcomes derived from the previously outlined methodology.

Figure 3.3 depicts the energy contents of waste heat across various Belgian industrial sectors, juxtaposed with their corresponding Carnot potential. The details of the acronyms used in the Figure can be found in table 3.1. In terms of energetic content, the Chemical & Petrochemical and Food & Tobacco sectors both exhibit the highest waste heat potentials. As anticipated, the Carnot potential consistently falls below the computed energy content.

The sectors exhibiting the most promising waste heat Carnot potential include **Non-metallic Minerals**, **Chemical and Petrochemical**, **Food and Tobacco**, **Paper**, as well as **Iron and Steel** sectors.

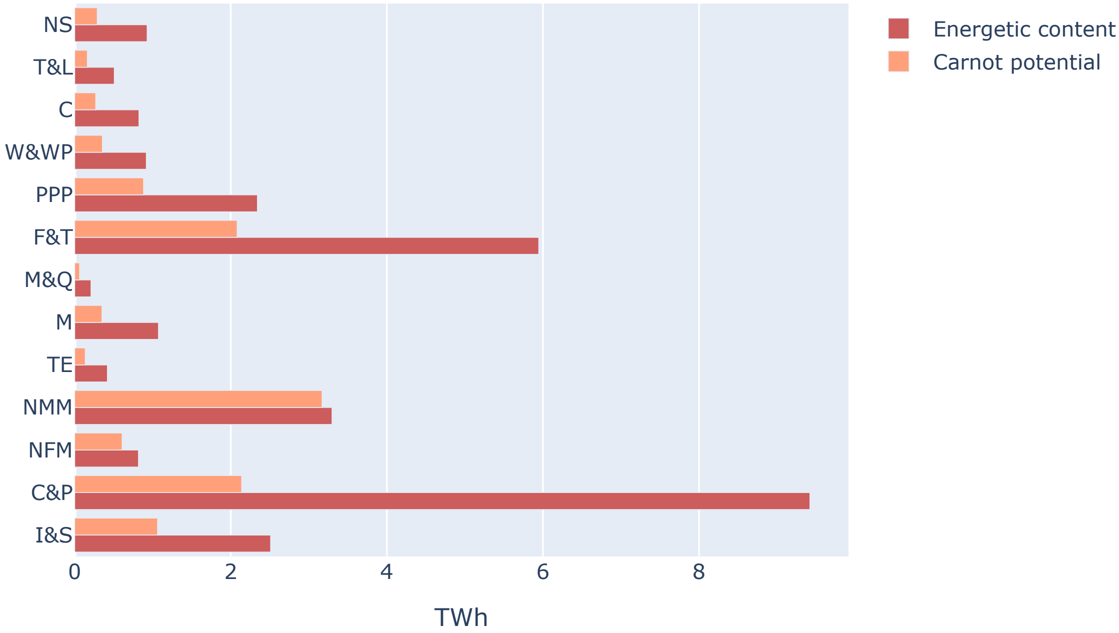


Figure 3.3 Industrial waste heat in Belgium per sector: energetic content and Carnot potential

As emphasized in the preceding chapter, the characterization of the temperature of exhaust and effluent streams holds great importance. This characterization is fundamental in delineating the disparities in Carnot waste heat potential across various temperature ranges. Furthermore, it also plays a crucial role in determining the suitability of a recovery technology. Figures 3.4 and 3.5 depicts this temperature characterization per industrial sectors, regarding the energetic content and Carnot potential of the thus estimated waste heat.

Figure 3.4 depicts the temperature characterization of the waste heat energetic content. It becomes evident that low-temperature waste heat accounts for a significant portion across all sectors, comprising **45% of the industry's total waste heat energy content**. In their Global Waste Heat Potential characterization, Forman et al. [1] estimated the low-temperature waste heat share of the industry to be 42%, while Bianchi et al. [3] estimated it to be 51%, validating the range of this analysis estimation.

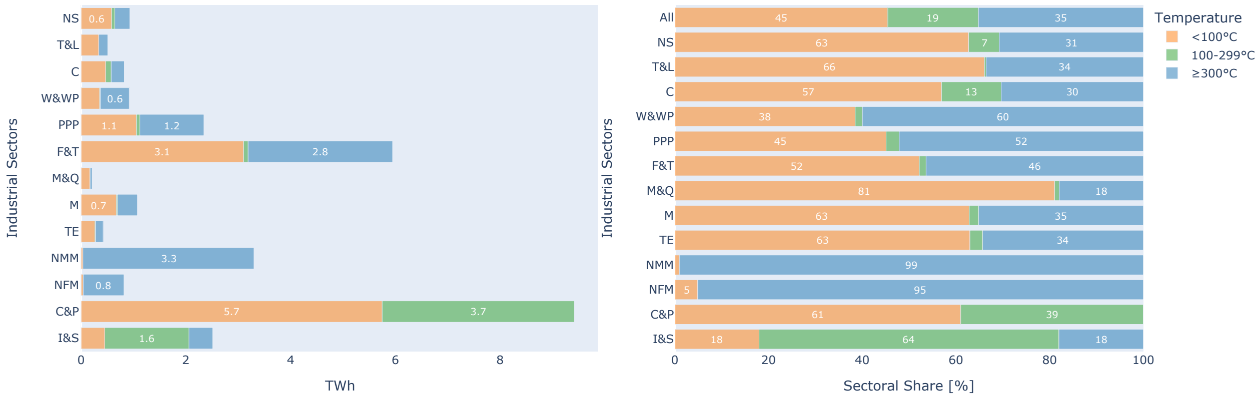


Figure 3.4 Energetic content of Industrial Waste heat: temperature characterization and share per sector.

Overall, the conducted analysis, based on the provided database, indicates that the high and medium temperature share of the waste heat are mainly due to the use of burners (whether oil, gas or coal) and diesel engines, the respective indicated exhaust gas temperatures being 300°C and 200°C [1][15]. In the Non-Ferrous Metals, it is mostly due to melting furnaces (exhaust temperature of 1000°C), while, in Non-Metallic Mineral, it is linked to the Cement and Glass production (exhaust temperature of 360 and 650°C).

All other sectors, except Non-metallic Minerals, Iron and Steel and Non-Ferrous Metals, exhibit substantial quantities of low-temperature waste heat in terms of energy content.

Upon reviewing the Carnot potential temperature characterization depicted in Figure 3.5, a notable shift is observed. The proportion of low-temperature waste heat Carnot potential across all sectors diminishes significantly, accounting for only 23%. Notably, the three sectors showing the highest Waste Heat Carnot Potential are the **Chemical & Petrochemical** (1 TWh), **Food & Tobacco** (0.7 TWh), **and Paper, Pulp, and Print** (0.3

TWh) sectors.

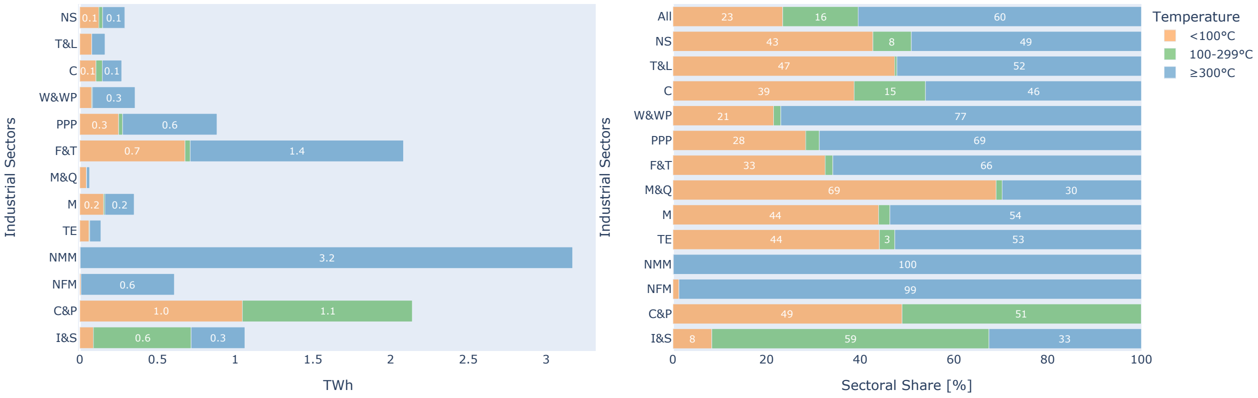
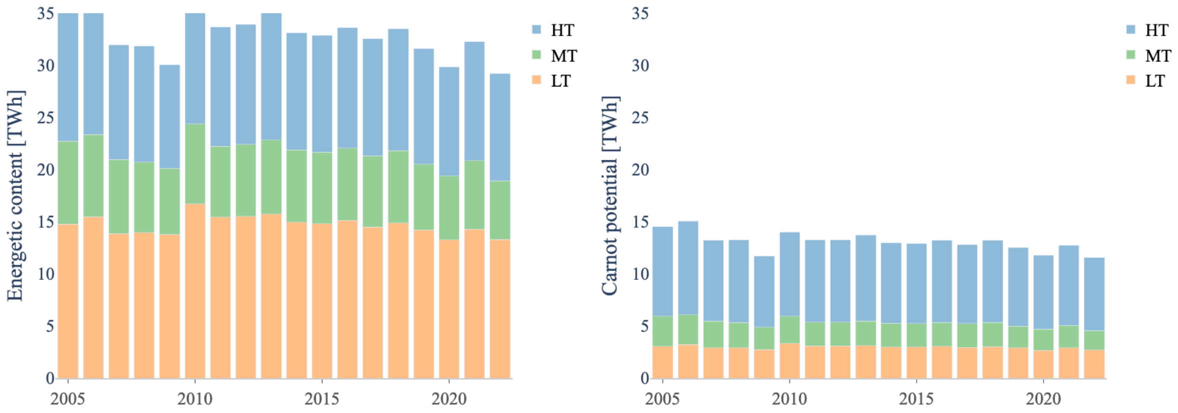


Figure 3.5 Carnot potential of Industrial Waste heat: temperature characterization and share per sector.

In terms of sectoral contributions to low-temperature waste heat, the Mining & Quarrying sector stands out with the highest share of low-temperature Carnot potential. However, despite this, the sector's overall contribution to waste heat potential remains relatively insignificant due to its limited activity in Belgium. As this analysis focuses on the global harvesting of low-temperature waste heat, a detailed examination of this sector's potential on a broader scale is not pursued. Nevertheless, the localized potential within this sector merits further investigation at the company level.

Characterizing the evolution of industrial waste heat over the years is of significant interest, particularly for its recovery potential. By adapting the balance factors based on yearly improvements since 2005, it is possible to evaluate the waste heat over time, as well as its Carnot potential equivalent. These evaluations are depicted in Figures 3.6a and 3.6b. In almost 20 years, it can be observed, that even though the waste heat energy content slightly diminished (from 35 to 30 TWh), its Carnot potential remains consistent. This is even more true regarding its low-temperature compound, which remains roughly at 2.4 TWh over the years. With more than 10 TWh of possible technical work, and assuming an heat-to-power conversion efficiency of 50 %, this would lead to nearly 6 TWh of electricity, representing 15% of the annual electricity consumption of the Belgian industry.



(a) Industrial waste heat energy content **(b)** Industrial waste heat Carnot potential

Figure 3.6 Historical evolution and temperature characterization of Industrial Waste heat

Figure 3.7 depicts the overall sectoral conversion of energy into energy services, other losses (dissipative), and waste heat. This latter is differentiate between its three temperature level, and further subdivided into its Carnot potential and non recoverable heat potential.

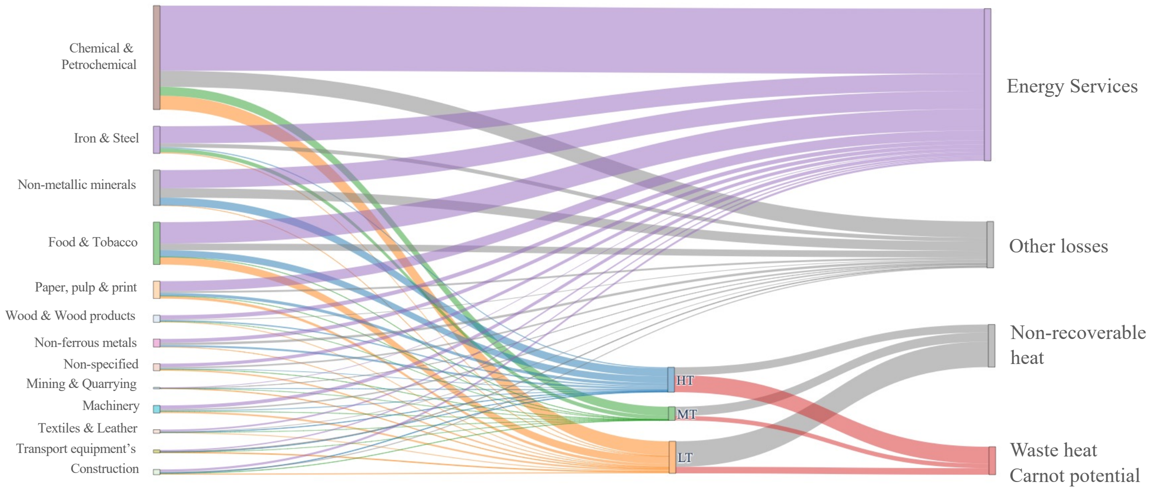


Figure 3.7 Overall Industry sectoral Energy balances

In the frame of waste heat recovery potential, the results findings are very clear: the three sectors to investigate are, by order importance, the Chemical and Petrochemical (C&P), the Food & Tobacco (F&T), and the Paper, pulp and print (PPP) sectors. The characterization conducted revealed that those losses predominantly occur the forms of effluents among the processes listed in Table 3.4.

Sector	Process	Energy source	WH temperature [°C]
C&P	Gasifier	Oil products	100
	Oil burner	Oil products	50
	Steam reformer	Natural gas	85
	Motors	Electricity	55
	Compressors	Electricity	80
F&T	Unspecified engines	Natural gas	85
	Motors	Electricity	55
	Compressors	Electricity	80
PPP	Unspecified engines	Natural gas	85
	Motors	Electricity	55

Table 3.4 Main processes responsible for low-grade waste heat generation, and their corresponding energy sources and effluent temperatures.

Three different temperature ranges are therefore clearly identified:

- 50-55°C for electrical motors effluents and burner effluents.
- 80-85°C for compressors and natural gas-fed engine effluents.
- 100°C for gasifier effluents - solely encountered in the Chemical & Petrochemical sector.

The industrial waste heat recovery potential shall therefore mostly be investigated within these processes.

4

Waste heat recovery: preliminaries

FACILITATING waste heat management within industrial processes requires the establishment of a systematic protocol. Analogous to the waste management hierarchy outlined in the European Directive of 2008 [16], a structured framework can guide the prioritization of interventions to optimize practical outcomes.

Primarily, emphasis is placed on preemptive measures aimed at limiting the generation of superfluous waste heat by identifying potentially unused energy services. Subsequent to this, the strategic reuse of waste heat within these processes emerges as a viable strategy for diminishing primary energy requirements, notwithstanding the potential necessity for substantial technological adaptations. Eventually, the exploration can extend to the prospect of employing additional technologies to recover waste heat in different ways, broadening the scope of potential solutions.

Figure 4.1 Waste heat management hierarchy

This chapter aims to provide a comprehensive exploration of the technological possibilities for waste heat recovery, with a particular focus on methods suited for low-grade energy sources. Additionally, it delves into the various barriers and complexities inherent in the deployment of such recovery mechanisms.

4.1 Recovery technologies

Waste heat recovery technologies encompass a variety of approaches, which can be organized into distinct categories based on their underlying principles. In their study *Economic analysis of heat transformation technologies*, Bruckner et al. [17] outlined a classification system illustrated in Figure 4.2.

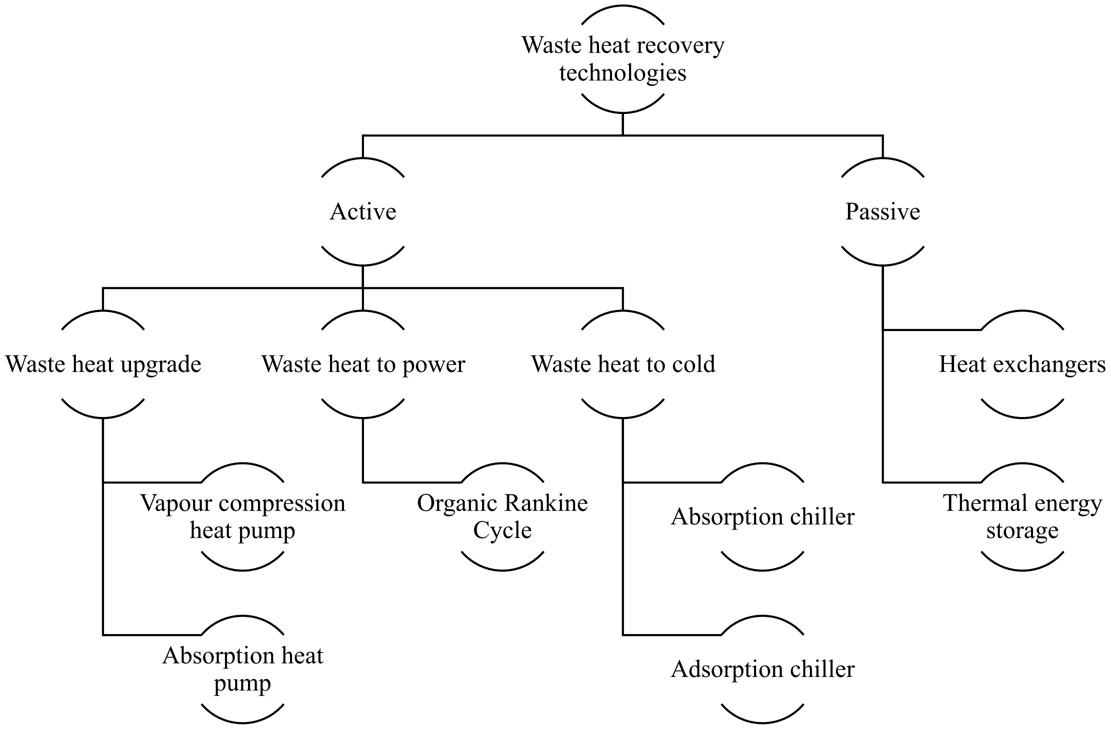


Figure 4.2 Categorization of low-temperature waste heat technologies, based on [17]

They initially divided these technologies into two primary categories: "Active-Passive." The classification is primarily based on whether the technologies convert waste heat into another form of energy or elevate its temperature -*Active* - or whether they utilize the waste heat directly at its existing temperature or at a lower level - *Passive*.

The subsequent sections explore four distinct possibilities: waste heat upgrading, the conversion of waste heat into electricity (known as waste heat to power), waste heat utilization for cooling purposes, and thermal energy storage.

4.1.1 Heat upgrade

One can initially consider recovering waste heat directly as heat without converting it into other forms of energy. However, as previously noted, most waste heat is generated at low temperatures, complicating its direct use since industrial process heat typically requires temperatures above 80°C [18]. The grade of heat, that can be defined by its ability to perform technical work, is primarily determined by its temperature. Technologies like heat pumps have been developed to elevate the temperature of this waste heat, thereby increasing its exergetic content.

To characterize the performance of heat pumps, the Coefficient of Performance (COP) is used, relating the heating capacity (Q_{out}) of the machine to the power required to drive it (W_{in}).

Heat pump Coefficient of Performance

$$COP = \frac{Q_{out}}{W_{in}}$$

There exist several types of heat pumps, with different compression working principles: Vapor Compression Heat Pump (VCHP), Absorption Heat Pump (AHP), Chemical Heat Pump, or even Transcritical Heat Pump.

Vapor compression heat pump

This first type of heat pump is largely adopted on an industrial level thanks to its low cost and simple operation [19]. A working fluid, more specifically a refrigerant, circulates between a heat source and a heat sink, passing successively through an evaporator, a compressor, a condenser, and eventually a flash valve. The refrigerant undergoes an isothermal phase change in the two heat exchangers, which allows the recovery of its energy.

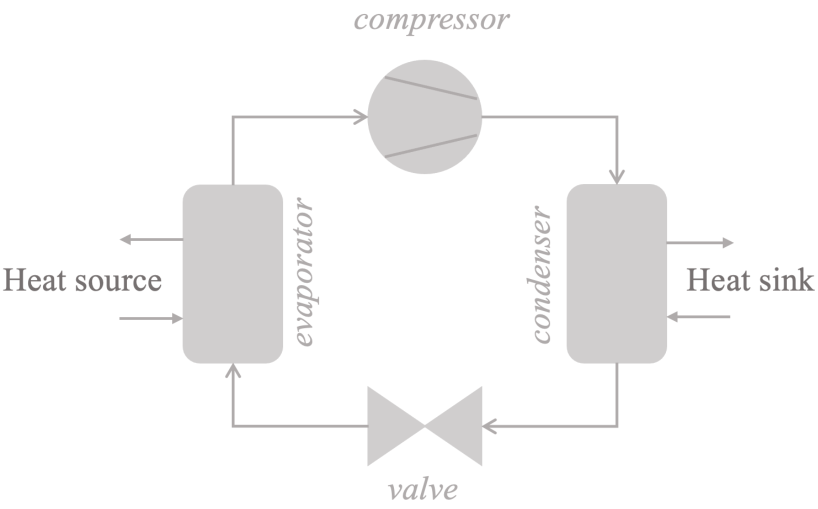


Figure 4.3 Vapour Compression Heat Pump

Its low heating capacity led to developing systems improvements, among which the multistage, or the cascade heat pumps [19]. Dividing the compression work between several compressors, and placing a separation tank in between, allows higher refrigerant flow, the density of the working fluid being indeed kept limited. Moreover, cascade heat pumps allow intermediate temperature heat recovery, which increases the overall performance of the machine.

Absorption heat pumps and heat transformers

Absorption heat pump (AHP), also known as Compression-Resorption Heat Pump or Hybrid Heat Pump, swaps the traditional refrigerant working fluid for an absorption pair such as $NH_3 - H_20$. The system, depicted in Figure 4.4, requires several components, among which an evaporator and a generator, to which heat is provided, as well as a solution heat exchanger, a condenser and an absorber.

The heat source, in our case waste heat, is mobilized to evaporate water flowing through an evaporator and to generate steam in a generator. The absorber plays a key role in the performance of the system since the upgraded heat is recovered from it, determining therefore the heating capacity.

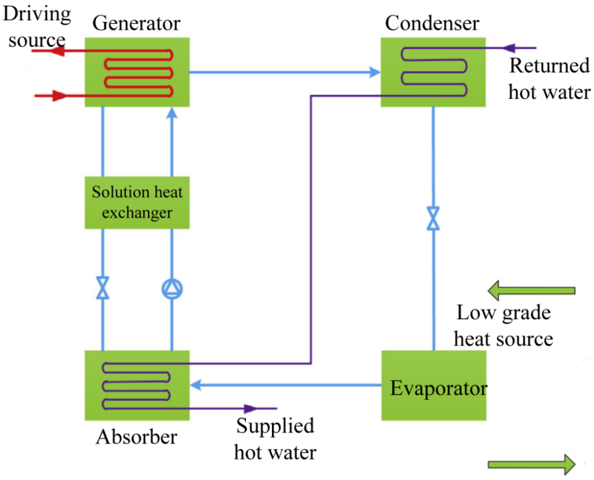


Figure 4.4 Absorption Heat Pump [20]

Compared to VCHP, Absorption Heat Pumps can operate at higher temperature with relatively low operating pressure. Moreover, they can achieve higher COP, with at least 20% energy performance gains [21].

Transcritical heat pump

The working fluid can also go through a supercritical state, in addition to a subcritical one. It is the basis principle of Transcritical Heat Pumps (THP), typically using CO_2 as a refrigerant. The system equipment has to undergo higher working pressure, resulting in an increased machine cost. However, it allows better efficiency as well as an increased temperature lift.

4.1.2 Heat-to-power

Direct utilization of waste heat is often impractical or unnecessary on site, and transporting it poses significant challenges. Therefore, converting this heat into electricity can greatly expand its potential applications. However, it is crucial to consider the efficiency of converting heat to power. This process is subject to substantial exergetic losses and even greater energy losses, particularly when dealing with low-temperature heat sources.

Organic Rankine Cycle

This engine cycle, comprising a condenser, an evaporator, a pump, and a turbine, relies on an organic fluid. By vaporizing this fluid at high temperatures and expanding it through a turbine, mechanical work can be recovered. Organic fluids, with their low boiling points, are more suitable for efficient low-temperature waste heat recovery compared to water. Using water at the same operating temperature would necessitate much lower pressures, posing significant technological challenges related to machine sealings. But most importantly, a lower pressure implies lower water density, which requires the volumetric machines to exert more effort.

The efficiency of those cycles, denoted as η_{ORC}, is determined by the net retrievable mechanical power (W_{net}) - the difference between the turbine work (W_{turb}) and the work required by the pump (W_{pump}) - which is compared to the evaporator heat input (Q_{evap}).

Organic Rankine Cycle efficiency

$$\eta_{ORC} = \frac{W_{net}}{Q_{evap}} = \frac{W_{turbine} - W_{pump}}{Q_{evap}}$$

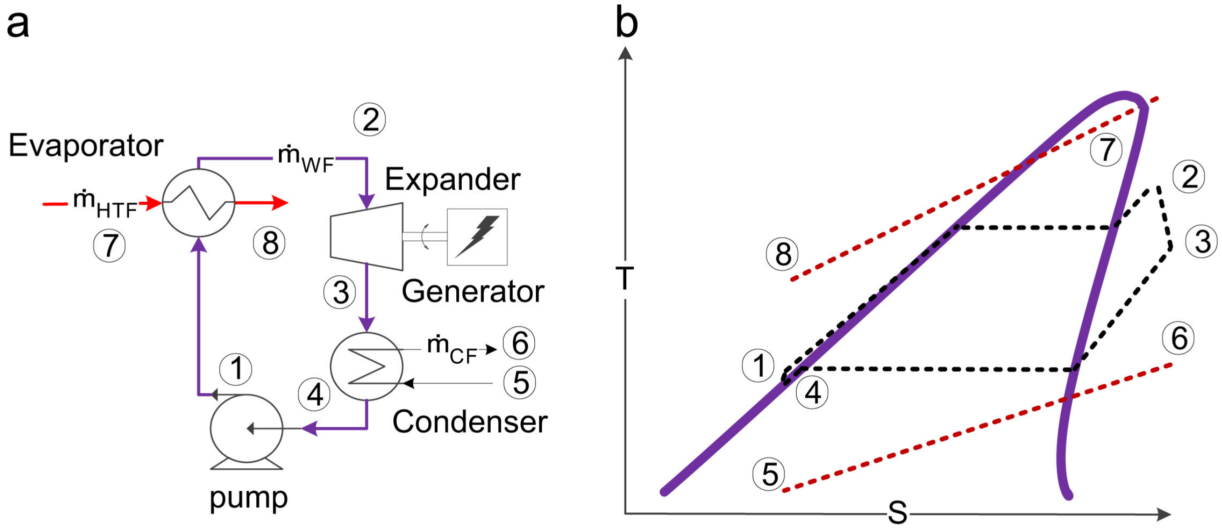


Figure 4.5 Subcritical ORC layout (a) and T-S diagram (b), reproduced from [22]

One could also envision using zeotropic fluids, which are composed of several substance with different boiling points. This leads to non-isothermal heat addition and heat rejection, which allows a better matching with the heat sources and heat sinks. It increases greatly the heat transfer, and diminishes the external irreversibilities.

4.1.3 Refrigeration

Waste heat recovery is also envisionned to drive cooling systems, the two most common technologies being the absorption and adsorption refrigeration systems.

Absorption refrigeration

The absorption refrigeration system requires the same components as the absorption heat pump depicted in Figure 4.4. It utilizes as well an absorbant-refrigerant pair, such as $NH_3 - H_2O$ or $H_2O - LiBr$. Low-temperature waste heat is now used as a driving heat source, while the evaporator retrieves heat from the environment.

Adsorption refrigeration

On the other hand, adsorption chillers utilize solid adsorbents, such as silica gel or zeolites, to adsorb and desorb a refrigerant using waste heat. Both adsorption and absorption chillers convert waste heat into useful cooling, enhancing energy efficiency and minimizing the need for additional energy sources for air conditioning or refrigeration.

4.1.4 Thermal Energy Storage

With the idea of solving the mismatch between the heat source and heat demand, one can implement Thermal Energy Storage (TES) systems using sensible, latent or thermochemical heat storage.

Sensible TES

Sensible Thermal Energy Storage involves the storage and discharge of heat in a medium, resulting in an increase or decrease in its temperature. This process occurs within the same phase, whether solid or liquid - water being a commonly used medium due to its low cost and high specific heat capacity. It is however important to note that storing heat at high temperatures in water necessitates high pressure to prevent phase change, whereas solids do not require such operating conditions.

There therefore exist several types of STES depending on the temperature range to reach. Water represents a cheap storage solution, with temperature lower than 100°C. At higher temperatures, molten salts and packed beds are more common. Molten salts, such as a mixture of sodium nitrate and potassium nitrate, are heated, stored in insulated tanks, and passing through a heat exchanger for heat retrieval. On the other hand, packed bed TES stores heat by passing a heated fluid through solid materials like rocks. This heat is later retrieved by reversing the fluid flow.

Latent TES

In Latent Thermal Energy Storage, the charging or discharging of heat from the storage medium is associated with a phase change. The materials utilized for this purpose are known as Phase Change Materials (PCMs). Heat transfer in this process is nearly isothermal, thereby minimizing heat transfer irreversibilities. Despite having a higher specific energy than Sensible TES, Latent TES systems entail significant installation and storage costs [23].

Chemical TES

With the idea that a chemical reaction can release or absorb thermal energy, heat can be stored through the separation of a chemical pair and released through its association. Such systems offer three advantages: they can operate at atmospheric pressure, possess a notably high energy density, and entail relatively low installation costs. However, their cost per unit of energy stored is the highest among the considered storage methods.

Summary of TES

Table 4.1 summarizes the main aspects of the previously detailed Thermal Energy Storage solutions

TES	**Capacity [MW]**	**Energy density [kWh$_t$/t]**	**Max. Temp [°C]**	**Costs [$/kWh]**		**Material and Temp. [°C]**
				Installation	**Storage**	
Sensible	0.1–10	10–50	500	3400-4500	0.1-10	Water (150) Rocks (900) Oil (150)
Latent	0.001–1	50–150	660	6000-15000	10-50	Ice (0) Molten salts (400) Metallic (500)
Chemical	0.01–1	150–250	180	1000-3000	8-100	NaOH (150) LiCl (100) Zeolite (180)

Table 4.1 Main Thermal Energy Storage types [23][24]

4.2 Waste heat utilization barriers

Despite the numerous technological solutions available for waste heat utilization, manufacturing companies do not always capitalize on this opportunity, even though it could enhance efficiency. They encounter various obstacles, including regulatory and financial barriers commonly associated with the implementation of new technologies, as well as technological challenges. Brueckner et al. [2] have summarized these challenges and provided potential solutions to address them.

Barriers	Potential solutions
Technological	
No nearby heat sink	Building heating pipes, heat transport.
No information about the heat sinks nearby	Waste heat exchange (information portal).
Time discrepancy of generation of heat and demand	Storage, waste heat to power for in-house use or feeding the grid.
Temperature level (mostly too low)	Heat pumps.
Production process	
Disturbance of the operation	
Production reliability	
Financial and administrative barriers	
Availability of investment funds	Subsidies, loans.
Priority of the core business	Use of service providers, waste heat contracting.
Too high rate of return expectations	Information about life cycle costs.
Uncertainty of the economic future	
Information	
Lack of business knowledge and personnel	Information campaigns and technology-specific training courses for selected target groups.

Table 4.2 Waste heat utilization barriers [2]

It is worth noting that the non-recovery of waste heat is linked to multiple factors, not only technological but also potentially due to a lack of heat demand at the time and place the waste heat is generated. As previously mentioned, although it is not the simplest solution, energy communities could be established to value waste heat as an exchangeable resource and transport it for use. Alternatively, waste heat could also be stored for later use in processes, or converted into electricity.

Combining these two latter ideas, what if waste heat could be utilized in electrical storage technologies? This would significantly contribute to the flexibility of the electrical grid, especially in the context of integrating renewable energy into our energy systems.

4.3 Carnot Battery

The Carnot Battery, also known as Pumped Thermal Energy Storage, is an emerging electrical energy storage technology. When electricity production exceeds demand, the surplus can be stored by powering a heating cycle that upgrades heat from a heat source to a thermal storage. A power cycle is subsequently employed to convert the stored heat back into electricity when needed. Its working principle is depicted on Figure 4.6.

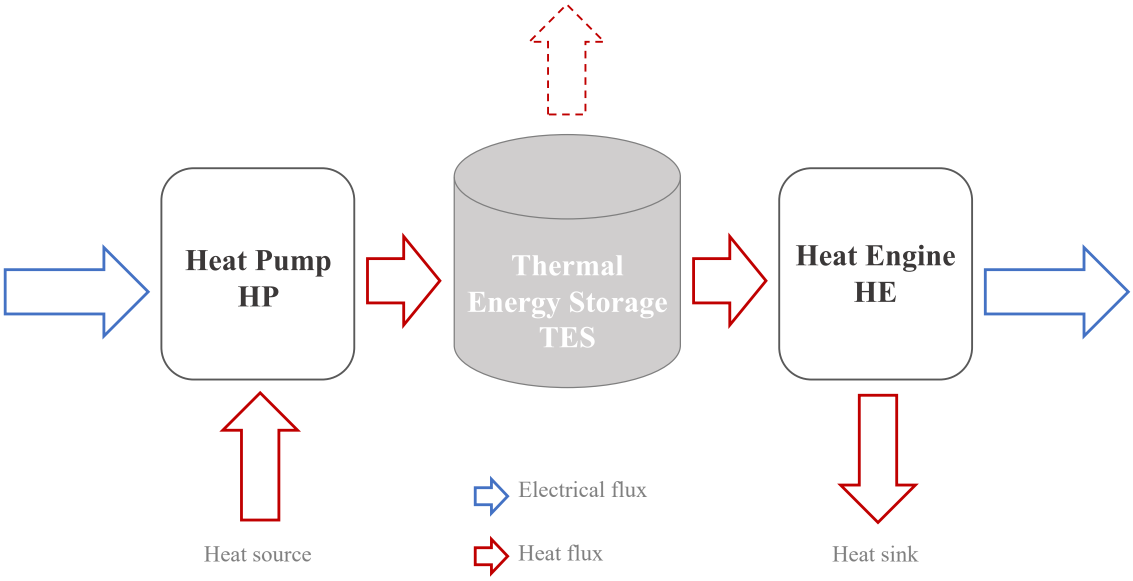


Figure 4.6 Carnot Battery concept

Several heat sources can be utilized, including ambient air, low-grade heat sources, and waste heat. When waste heat is recovered as so, the system is referred to as Thermally Integrated Pumped Thermal Energy Storage (TI-PTES).

In addition to electrical storage capabilities, these systems can also recover heat at the thermal energy storage unit, providing added flexibility. Various configurations of these systems exist, depending on the machines employed and the type of storage used.

4.3.1 Performance

The performance of such systems can be evaluated using several key performance indicators.

The **Power-to-Power efficiency** (η_{p2p}), also known as **Roundtrip Efficiency** (RTE), measures the ratio of electrical output from the Heat Engine to the electrical input to the Heat Pump, thus indicating the quality of the storage process. TI-PTES systems were besides developed with the idea of enhancing η_{p2p}, utilizing higher grade heat sources, specifically waste heat streams. This lead to η_{p2p} reaching a value even higher than 100%.

But in the case of TI-PTES, it is necessary to express the quality of waste heat as part of the performance indicator. The **exergy efficiency** η_{ex} aims to account for both heat recovery and electricity storage efficiency.

Storage compactness can be assessed by evaluating the **Energy Storage Density** (ESD), which relates the electrical output of the system to the storage volume or mass.

Attention should also be given to energy losses during the standby phase, when thermal energy is stored. The **Self-Discharging Rate** (SDR) quantifies this by relating the electrical energy output of the system to the energy lost during the standby period.

Lastly, the overall cost of such systems can be quantified by evaluating the **Levelized Cost of Storage** (LCOS), which considers investment costs, operational and maintenance costs, and the discount rate.

4.3.2 Classification

There exist several configurations of such systems, utilizing different layouts, components, and storage types.

Brayton-based

The Brayton-based Carnot Battery utilizes an inverse Brayton cycle as heating cycle, a Brayton Heat Engine, and two Sensible Thermal Energy Storage reservoirs operating at high and low temperatures, most usually being packed-beds [25].

Excess electricity intended for storage is used to compress a gas, thereby transferring heat from the low-temperature (LT) reservoir to the high-temperature (HT) reservoir. During the discharge phase, the enthalpy difference between the two reservoirs drives an expander, generating work and partially recovering the input electrical energy.

In addition to having a notably high energy storage density, the high operating temperatures of the Carnot Battery - usually well above 200°C [23] - contribute to an elevated Power-to-Power efficiency. However, this efficiency is highly sensitive to the polytropic efficiency of the turbomachines: even a slight decrease can reduce η_{p2p} from 60-70% to a value as low as 35% [23]. Furthermore, these high temperatures result in increased costs.

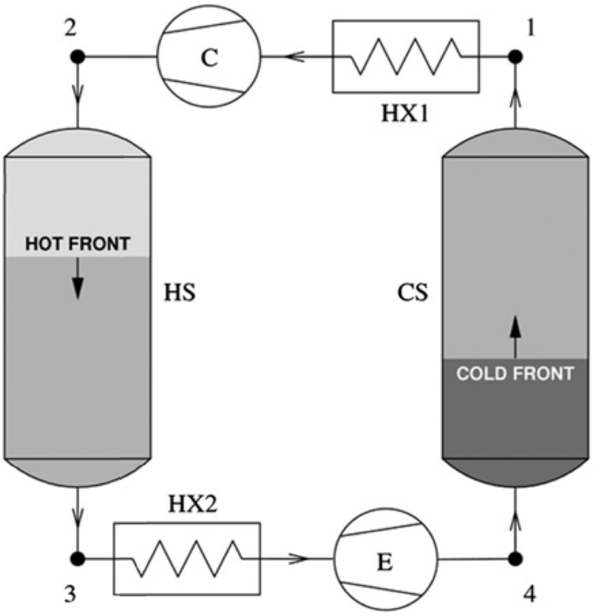


Figure 4.7 Brayton-based Carnot Battery with packed beds, reproduced from [25].

Rankine-based

A Rankine-based Carnot battery is an energy storage system that utilizes Rankine cycles, including steam, organic Rankine (ORC), and trans-critical CO2 cycles, to store and release energy. The process involves compressing a working fluid at high pressure, recovering both sensible and latent heat from a hot reservoir, driving turbines to generate electricity, and finally condensing the fluid back to a liquid state. These systems can achieve round-trip efficiencies ranging from 40% to 70%, and can exceed 100% when incorporating external low-grade or waste heat sources. Various configurations have been studied, such as cascade ammonia-water and CO2 cycles, which optimize thermal layouts and use phase change materials for energy storage. Rankine-based Carnot batteries are advantageous for their lower operating temperatures, and compatibility with existing commercial equipment, making them suitable for large-scale applications.

Liquid Air Energy Storage - LAES

Liquid Air Energy Storage (LAES) is an energy storage technology that stores energy by liquefying air. It consists of three main components: a liquefaction unit, a storage section with cryogenic tanks, and a power recovery unit. During the charging phase, electricity is used to compress and cool ambient air to cryogenic temperatures, producing liquid air which is then stored in cryogenic tanks. During discharge, the liquid air is pumped to high pressure, evaporated, and heated using thermal stores or external heat sources. It is then expanded through turbines to generate electricity. LAES systems can achieve round-trip efficiencies (RTE) between 40% and 60%, which can be further increased to 70-80% by integrating additional processes such as absorption chillers, Rankine, or Brayton power cycles. Key advantages of LAES include higher energy density and lower operating pressures. Additionally, recycling compression heat and utilizing waste heat or cold can further enhance its efficiency.

Carnot Battery types - performances comparisons

Figure 4.8 aims to compare the differents performance indicators detailed in Section 4.3.1 between the different Carnot Battery types presented.

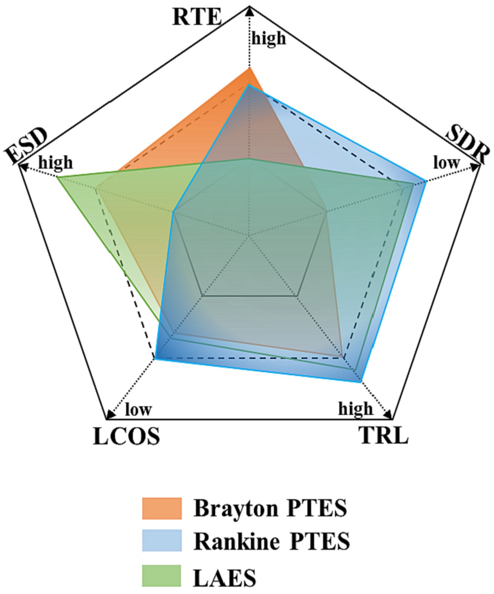


Figure 4.8 Advantages and Disadvantages of different Carnot Battery types, from [26] (RTE: Round-trip-efficiency, SDR: Self-discharging rate, TRL: Technology Readiness Level, LCOS: Levelized Cost Of Storage, ESD: ENergy Storage Density)

5

Potential of Industrial low-grade waste heat recovery in Belgium

WASTE heat potential investigation of Chapter 2 has identified three sectors with significant waste heat Carnot potential: Chemical & Petrochemical, Food & Tobacco, and Paper, pulp and print. While the preceding chapter discussed various waste heat recovery technologies, this chapter delves into the recovery potential of low-grade waste heat within these sectors through the integration of three distinct recovery technologies: the Heat Pump, the Organic Rankine Cycle, and the Carnot Battery.

The constraints surrounding waste heat integration will firstly be outlined, followed by the examination of the three recovery scenarios. Each of them will delineate the chosen methodology and the resultant findings, which will later be discussed.

5.1 Waste heat integration

Recovering low-grade waste heat in these three sectors presents challenges, particularly due to its predominant occurrence in the form of effluents. Forman et al. [1] define these effluents as losses occurring in coolant services, which affect the heat recovery from these streams by impacting the temperature glide of such heat sources.

The temperature glide (ΔT_{gl}), denoting the temperature reduction of a stream after its heat extraction, holds indeed significance in this context. Heat recovery may indeed occur under either free or fixed glide conditions. Free glide conditions allow for heat source temperature reduction without constraints. This situation arises, for example, in cooling towers or with exhaust gases intended for release into the environment. Conversely, limitations may exist on the degree to which the temperature of the waste heat stream can be reduced, and its glide may be fixed.

Determining whether the encountered situation falls under free or fixed glide conditions is fundamental, as it influences the chosen model to describe the system and affects the performance of the recovery technology. For instance, in heat pump integration, recovery under free glide conditions can ensure effective waste heat recovery but will negatively impact heat pump performance by reducing the temperature at which the working fluid evaporates, thereby lowering the Coefficient of Performance.

Considering the previously identified low-grade waste heat streams, predominantly occurring within cooling systems, recovery was assumed to occur under fixed glide conditions. Substantially lowering the temperature of the effluent stream in a closed cooling circuit could indeed impose significant thermal stress on equipment and compromise desired cooling conditions. Recovering heat under free glide conditions could likely require additional process adaptation.

A fixed waste heat glide of 10K was assumed [27], which, as previously mentioned, can be advantageous from the perspective of heat pump performance.

5.2 Heat pump potential

As mentioned in the previous chapter, waste heat can be recovered and upgraded by the integration of heat pumps downstream of industrial processes. This section aims to describe and analyze the heat pump potential in the three investigated industrial sectors.

5.2.1 Methodology

Heat pump model

Waste heat recovery through heat pump integration was investigated for different temperature lifts going up to 100K.

One can use the Coefficient of Performance of heat pumps to derive the electrical power required to upgrade heat at the process temperature. The maximum theoretical value of this coefficient can be expressed as a function of the source and sink temperatures (Equation 5.1). Considering the temperature glide of the heat streams, the logarithmic mean temperatures of the two streams T_{LM} need to be expressed. This depicts the Lorenz model, used in situations where the heat sink and heat source temperature glides can not be neglected. If they could, one could use the Carnot model, and the logarithmic mean temperatures of Equation 5.1 should be replaced by the constant heat source and sink temperatures. However, since our model considers the temperature glide of both the heat source and heat sink, the choice of Lorenz *COP* appears to be more appropriate.

Yet, due to various thermodynamic losses, this upper bound is not representative of the real machine performance.

One can therefore use the corresponding second law factor η_{2nd}, which connects the actual and theoretical COP of the heat pump. In their market overview of High-Temperature Heat Pumps (HTHPs), Arpagaus et al. [18] reported the performances of 17 heat pumps, operating on experimental research studies. Depending on the heat sources and sink temperature, they identified second law factors, mostly falling in the range of 40-60%. For this heat pump model, the value of $\eta_{2nd,HP} = 50\%$ was therefore chosen.

This allows to retrieve the heat pump heat output $Q_{out,HP}$ as well as its power requirement $E_{e,in,HP}$, as expressed in Equation 5.3.

Heat pump performance

$$COP_{th} = \frac{T_{h,HP,LM}}{T_{h,HP,LM} - T_{c,HP,LM}} \quad \text{with} \quad T_{LM} = \frac{T_{in} - T_{out}}{log\left(\frac{T_{in}}{T_{out}}\right)} \tag{5.1}$$

$$COP = \eta_{2nd,HP} COP_{th} \tag{5.2}$$

$$\Longrightarrow \begin{cases} Q_{out,HP} = Q_{WH} \frac{COP}{COP-1} \\ E_{e,in,HP} = \frac{Q_{WH}}{COP-1} \end{cases} \tag{5.3}$$

For each process identified in the previous industrial waste heat characterization, the integration of a heat pump with a lift up to 100K was considered. As a reminder, they consist of three temperature ranges of interest: 50-55°C, 80-85°C and 100°C.

Since the heat source glide was set to 10K, as specified in Section 5.1 and the heat pump lift is set as well: it remains to determine the heat pump log mean temperatures, the *COP* and the heat pump energy output.

Heat coverage

To evaluate the potential of heat pump integration on an industrial level, it is fundamental to consider the heat process demand and temperature ranges of the investigated sector. Doing so is hardly achievable on the national level: research was for example conducted based on the manufacturing processes of individual plants and upscaled to the global level thanks to the plants' capacities as well as their operational hours [28].

For this analysis, given the unsuccessful attempts to gather information through company surveys, an alternative methodology was devised to assess the capacity of heat pumps to provide heat for industrial processes. The temperature distribution of general processes across multiple industrial sectors was summarized for the German industry in 2009 [29]. Assuming that the distribution of heat requirements across different temperature ranges has remained consistent from the German industry in 2009 to the Belgian industry in 2022, one can determine the heat requirement shares by temperature range for the three industrial sectors of interest.

Sector	**Hot Water [%]**	**Space heating [%]**	**Process heat [%]**					
			< 100°C	**100-200°C**	**200-300°C**	**300-500°C**	**500-1000°C**	**>1000°C**
C&P	0.21	6.91	13.92	9.79	6.08	5.67	46,08	11.34
PPP	0.86	23.71	33.71	39.14	2.57	0	0	0
F&T	0.66	15.89	17.88	37.09	1.32	27.15	0	0

Table 5.1 Heat requirements share by temperature range, based on [29]

Throughout the analysis and for simplicity's sake, the *Hot Water* and *Space Heating* requirements are considered as part of the process heat requirement at a temperature below 100°C. Additionally, across a specific temperature range, the heat requirement temperature distribution is assumed uniform, see Equation 5.5. The minimal requirement process temperature for each sector was set to 20°C [18].

The sectoral process heat can be calculated using the energy conversion efficiency of various fuels and their energy consumption (Eq. 5.4). For a given heat pump outlet temperature t, the sector's heat requirement at that specific temperature can be determined (Eq. 5.5), allowing for the computation of the overall Heat Coverage (HC) of the implemented heat pump relative to the sector's process heat requirement (Eq. 5.6).

Heat coverage

Process combustion heat

$$Q_{\text{comb}} = \sum_{\text{fuels}} FEC_{\text{fuel}} \eta_{\text{conv,fuel}} \tag{5.4}$$

Process heat coverage

$$Q_{\text{supply max,t}} = \alpha_t Q^{\text{ref}}_{\text{comb}} \frac{T_{\text{out,HP,LM}} - T_{\text{t,min}}}{T_{\text{t,max}} - T_{\text{t,min}}} \tag{5.5}$$

$$HC = \frac{Q_{\text{supply,tot}}}{Q^{\text{ref}}_{\text{comb}} (\alpha_{<100} + \alpha_{100-200})} \tag{5.6}$$

Savings

Quantifying the savings associated with the integration of heat pumps is crucial, particularly in terms of the reduction in fossil fuel usage and the decrease in carbon dioxide emissions. To achieve this, two scenarios were investigated, and the savings were measured relative to a scenario of reference, which assumes no integration of heat pumps. Scenario 1 represents the integration of heat pumps at an industrial level within the current Belgian energy system while Scenario 2 represents a fully decarbonized Belgian electricity system.

The two vary in the expression of three parameters. The **share of gross electricity consumption generated from renewable energy sources** β in Belgium is obtained from the Eurostat Renewable Energy statistics [30]. In 2022, this value was 29.106%, which is used for the first scenario. For the second scenario, this value is set to 1, assuming a fully decarbonized electricity production system.

It is also necessary to express the **Primary Energy Factor** (PEF), which links the amount of primary energy units required to produce a single unit of electricity (PEF_e) or heat (PEF_h). Naturally, PEF_h can be expressed as $PEF_h = 1/\eta_{conv}$. In Belgium, the current Primary Energy Factor for electricity is 2.1 [31], which is used in Scenario 1. In Scenario 2, a value of 1 is used, in line with the European Commission's Energy Efficiency Directive [32].

Lastly, **emissions associated with electricity generation** must also be considered. In 2022, the emission factor (EF_e) was 145 kg $\mathrm{CO}_{2,eq}/\mathrm{GWh}_e$ [33]. One can assume this value to be zero once a fully decarbonized system is achieved.

Scenario	$\beta[\%]$	$PEF_e[-]$	$EF_e\left[\frac{kgCO_2}{GWh_e}\right]$
1	29.11	2.1	145
2	100	1	0

Table 5.2 Scenarios and figures indicating the penetration of renewable into our energy systems

HP integration - Savings

Avoided fossil fuel

$$FEC_{\text{comb}}^{ref} = \sum_{fuels} FEC_{\text{fuel}}^{ref} \tag{5.7}$$

$$AFF^i = FEC_{\text{comb}}^{ref}\left(1 - \frac{Q_{\text{comb}}^i}{Q_{\text{comb}}^{ref}}\right) - E_{e,HP}\left(PEF_e^i - \beta^i\right) \tag{5.8}$$

Carbon Dioxide Emissions reductions

$$CDE_{\text{red}}^i = \frac{Q_{\text{supply,tot}}}{Q_{\text{comb}}^{ref}}\left(\sum_{\text{fuels}} EF_{\text{fuels}} FEC_{\text{fuel}}\right) - E_{\text{e,HP}} EF_{\text{e(i)}} \tag{5.9}$$

The emissions factors used in this analysis are expressed in Table 5.3.

Product	**EF** [t$CO_{2,eq}$/MWh]
Solid fuels	
Anthracite	0.395
Other bituminous coal	0.382
Coke oven coke	0.402
Solid biofuels	0.019
Waste	0.437
Liquid fuels	
LPG	0.287
Naphta	0.305
Motor gasoline	0.314
Fuel oil	0.320
Liquid biofuels	0.043
Gaseous fuels	
Natural gas	0.242

Table 5.3 Emission factors of fuels encountered in the three considered sectors [34]

5.2.2 Results

Depending on the process temperature range considered (50-55°C, 80-85°C, 100°C) and the sectoral heat and temperature requirements, the optimal heat pump integration conditions - meaning the heat pump lift in this analysis - will differ. The optimality of the implementation is evaluated based on its associated *Heat coverage*. The range of the retrievable heat pump output therefore varies greatly, and can be visualized in Figure 5.1.

It should be noted that the null potentials of the 100°C processes for the Paper, Print, and Pulp sector and the Food and Tobacco sector are merely related to the absence of such process in their previous sectoral characterization.

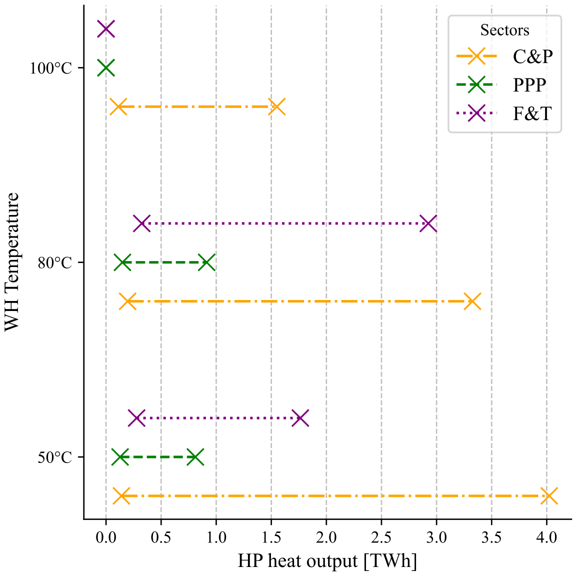


Figure 5.1 Sectoral HP heat output potential ranges per process temperatures.

Considering the most optimal integrations, we can outline the decrease in Fossil Fuel Usage (FFU) and Carbon Dioxide Emissions (CDE). As mentioned previously, both are quantified in the two scenarios detailed in Section 5.2.1, as well as in a reference situation where no heat pump integration is considered.

The heat recoverable from integrated heat pumps has the potential to substitute a substantial portion of the heat currently generated through fossil fuel combustion, resulting in significant reductions in CO2 emissions. These shares and their corresponding reductions can be characterized per sector and waste heat temperature range, as detailed in Tables 5.4, 5.5 and 5.6.

WH T° [°C]	Q_{HP} [TWh]	HC (<200°C) [%]	HC [%]	Scenario 1		Scenario 2	
				AFF [TWh]	CDE red. [Mt CO_{2eq}]	AFF [TWh]	CDE red. [Mt CO_{2eq}]
50-55°C	4.02	56.9	17.54	2.62	1.08	4.59	1.24
80-85°C	3.33	47.05	14.50	3.14	0.97	3.80	1.03
100°C	1.56	21.93	6.76	0.57	0.38	1.77	0.48
Total	**8.90**	**125.89**	**30.82**	**6.34**	**2.44**	**10.16**	**2.74**

Table 5.4 Chemical and Petrochemical Heat pump integration potential

WH T° [°C]	Q_{HP} [TWh]	HC (<200°C) [%]	HC [%]	Scenario 1		Scenario 2	
				AFF [TWh]	CDE red. [Mt CO_{2eq}]	AFF [TWh]	CDE red. [Mt CO_{2eq}]
50-55°C	0.81	19.07	18.58	0.004	0.04	0.94	0.11
80-85°C	0.91	21.48	20.93	0.33	0.07	1.06	0.13
100°C	-	-	-	-	-	-	-
Total	**1.72**	**40.55**	**39.51**	**0.33**	**0.11**	**1.99**	**0.23**

Table 5.5 Paper, pulp and print Heat pump integration potential

WH T° [°C]	Q_{HP} [TWh]	HC (<200°C) [%]	HC[%]	Scenario 1		Scenario 2	
				AFF [TWh]	CDE red. [Mt CO_{2eq}]	AFF [TWh]	CDE red. [Mt CO_{2eq}]
50-55°C	1.76	24.62	17.6	0.30	0.31	1.97	0.44
80-85°C	2.9	40.82	29.20	0.16	0.48	3.27	0.73
100°C	-	-	-	-	-	-	-
Total	**4.69**	**65.43**	**46.80**	**0.46**	**0.79**	**5.25**	**1.18**

Table 5.6 Food and Tobacco Heat pump integration potential

This analysis demonstrates the substantial potential for integrating heat pumps in the **Chemical and Petrochemical** sector for processes requiring temperatures below 200°C. Heat pumps could meet up to **125%** of the heat demand for sub-200°C processes and up to **30%** of the total heat demand in these sectors.
Similarly, the **Food and Tobacco** sector exhibits significant potential, with heat pumps capable of covering **65%** of the heat demand for processes below 200°C and up to **46%** of the total heat demand, reflecting the generally lower process temperatures compared to the Chemical sector.
Lastly, in the **Paper sector**, heat pump integration could meet **40%** of the heat demand for sub-200°C processes and up to **39%** of the overall heat demand.

In their study on the European Industrial Heat Pump Market Potential, Marina et al. [28] estimated the heat coverage achievable by heat pumps for heat requirements below 200°C across the former EU28 industry. Their analysis was based on data from several plants, including waste heat generation and heat requirements, extrapolated to a global level using plant capacities and annual operating hours. The results of their study differ from those obtained in this analysis. Specifically, this analysis indicates a higher heat coverage below 200°C for the Chemical and Food sectors and a lower heat coverage below 200°C for the Paper sector compared to Marina et al.'s findings. This could be due to the significantly different estimation approaches of the heat and temperature requirements of the investigated sectors.

Figure 5.2 presents the cumulative sectoral heat output from heat pumps (HP) and the corresponding sectoral Carbon Dioxide Emissions (CDE) for each scenario.

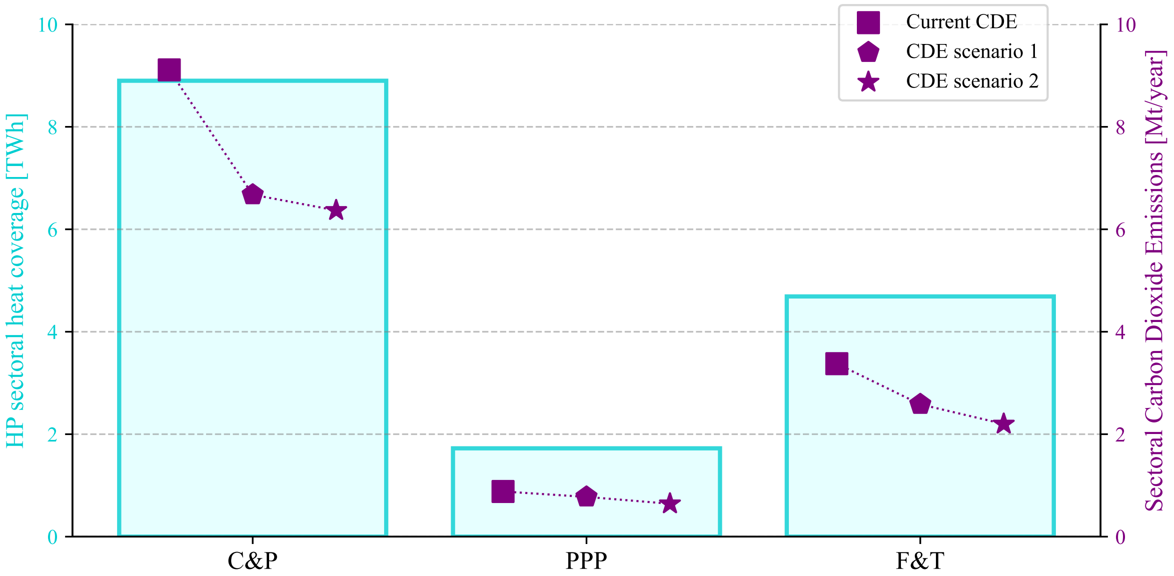


Figure 5.2 Sectoral heat coverage of the heat supplied by the integrated HP and the sectoral Carbon Dioxide Emissions depending on the scenario considered.

Concerning CO_2 emissions reduction, the integration of heat pumps demonstrates substantial potential in the Chemical & Petrochemical sector, as well as in the Food & Tobacco sector. If the decarbonization of the Belgian energy system further enhances this reduction potential, this enhancement is particularly marked in the Paper sector, where the reductions are of 12% in Scenario 1, and up to 27% in Scenario 2. The gain of heat pump integration in this sector is therefore particularly impacted by the decarbonization of electricity.

For a visual representation of the impact of heat pump integration on both Fossil Fuel Usage and sectoral electricity consumption, one should direct their attention to Figure 5.3.

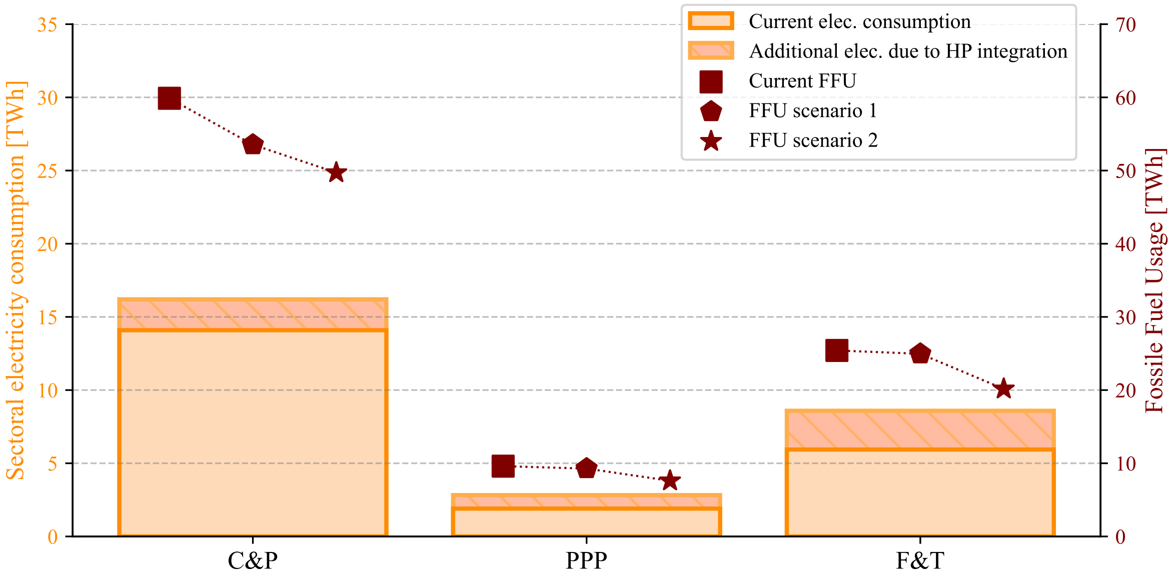
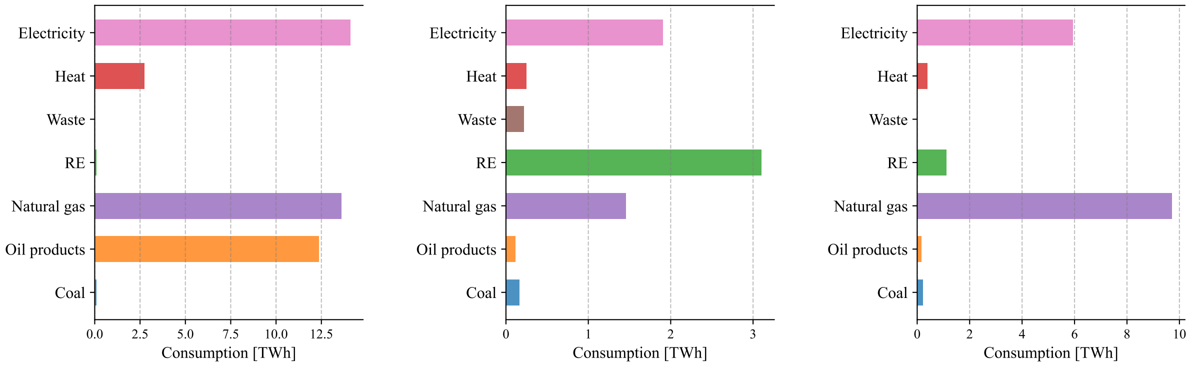


Figure 5.3 Sectoral electricity consumption with and without HP integration and sectoral Fossil Fuel Usage depending on the scenario considered.

The most substantial reductions in Fossil Fuel Utilization are observed notably in the Chemical sector. In terms of Fossil Fuel Usage reduction, one can note that, across all sectors, the decarbonization of the energy systems has a significant impact. It is especially visible in the Food and the Paper sectors, compared to the sole integration of Heat pumps.

Additionally, the influence of the energy mix on various sectors is apparent. Indeed, the sole integration of heat pumps has a significantly lesser impact on the Paper sector, the proportions of renewables and biofuels in the energy compositions of this sector already holding significance, as visible in Figure 5.4.



(a) Chemical and Petrochemical **(b)** Paper, pulp, and print **(c)** Food and Tobacco

Figure 5.4 Current energy mix of the sectors of interest

Consequently, in the absence of further decarbonization of the overall Belgian energy mix, the sole integration of heat pumps exhibits a constrained effect on diminishing fossil fuel usage, given its already comparatively low level.

Regarding the sectoral increase in electricity consumption, it is notably pronounced in the Food and Tobacco sector due to its high waste heat potential combined with lower waste heat temperatures, necessitating extensive upgrading.

Overall, the combination of heat pump integration and the decarbonization of the energy mix significantly diminishes Fossil fuel usage across all sectors, particularly in the Food & Tobacco sector.

5.3 Organic Rankine cycle integration

The recovery of low-grade waste heat as electricity can be achieved through the integration of an Organic Rankine Cycle (ORC). This section details the methodology used to assess the potential of ORC integration in the three considered sectors and analyzes the resulting findings.

5.3.1 Methodology

Organic Rankine Cycle model

Similarly to the heat pump model detailed previously, the objective was to derive the theoretical efficiency of the ORC based on the temperatures of the heat source and heat sink, and to relate this to the actual performance of the machine through its second law efficiency, $\eta_{2nd,ORC}$. Extensive research did not yield a specific value, it was therefore assumed to be 50%, following the approach taken by Marina et al. in their heat pump market potential study [28]. In Equation 5.10, the heat source temperature T_h corresponds to the waste heat temperature, while the heat sink temperature T_c corresponds to the ambient temperature.

Organic Rankine Cycle performance

$$\eta_{ORC,th} = \frac{T_{h,ORC,LM} - T_{l,ORC,LM}}{T_{h,ORC,LM}} \quad \text{with} \quad T_{LM} = \frac{T_{in} - T_{out}}{log\left(\frac{T_{in}}{T_{out}}\right)} \tag{5.10}$$

$$\eta_{ORC} = \eta_{2nd,ORC}\eta_{ORC,th} \tag{5.11}$$

$$W_{net,ORC} = \eta_{ORC}Q_{WH} \tag{5.12}$$

The ambient temperature was assumed to be 15°C, reflecting a reasonable average for Belgium, and the heat sink glide, $\Delta T_{amb,gl}$, was assumed to be 5K.

5.3.2 Savings

To assess the savings resulting from integrating an ORC to recover industrial process waste heat, one can quantify how much of the sectoral electricity consumption could be covered by the ORC's electricity supply. This can lead to determining the resulting Carbon Dioxide Emissions (CDE) savings, using the current electricity emission factor EF_e of Belgium - 145 kg $CO_{2,eq}/GWh_e$ [33]. The Carbon Dioxide Emissions reductions (CDE_{red}) induced by this integration can therefore be calculated as shown in Equation 5.13, where $E_{e,net,ORC}$ represents the net electrical energy output of the ORC.

ORC integration - Savings

$$CDE_{red} = E_{e,net,ORC} EF_e \tag{5.13}$$

5.3.3 Results

The performance of the ORC varies according to the waste heat temperature range. As indicated by Equation 5.10, the efficiency η_{ORC} increases with higher waste heat temperatures, which is also depicted in Figure 5.5.

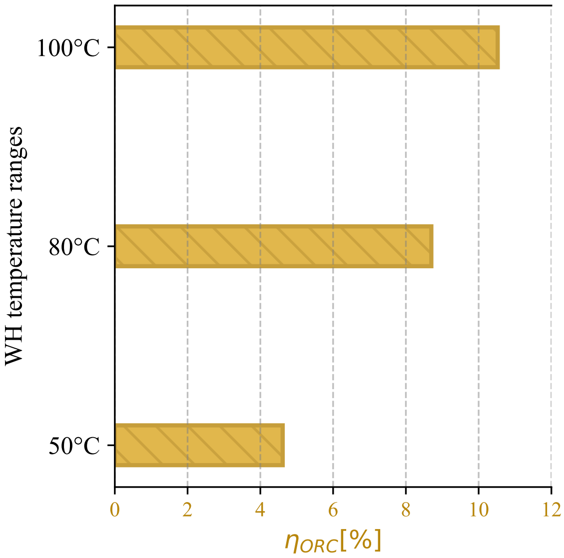


Figure 5.5 ORC efficiencies with regards to the waste heat temperature: the higher the temperature, the higher the efficiency.

Figure 5.6 depicts the electricity supplied by the thus integrated ORC and its coverage of the current electricity consumption per sector. Given the proportional relationship between the harvested waste heat and the ORC electrical output energy, it is unsurprising that the Chemical & Petrochemical sector shows the highest potential.
Regarding sectoral **electricity consumption coverage**, it is uniformly around **3 to 4% of the overall electricity consumption**, indicating a relatively limited impact.

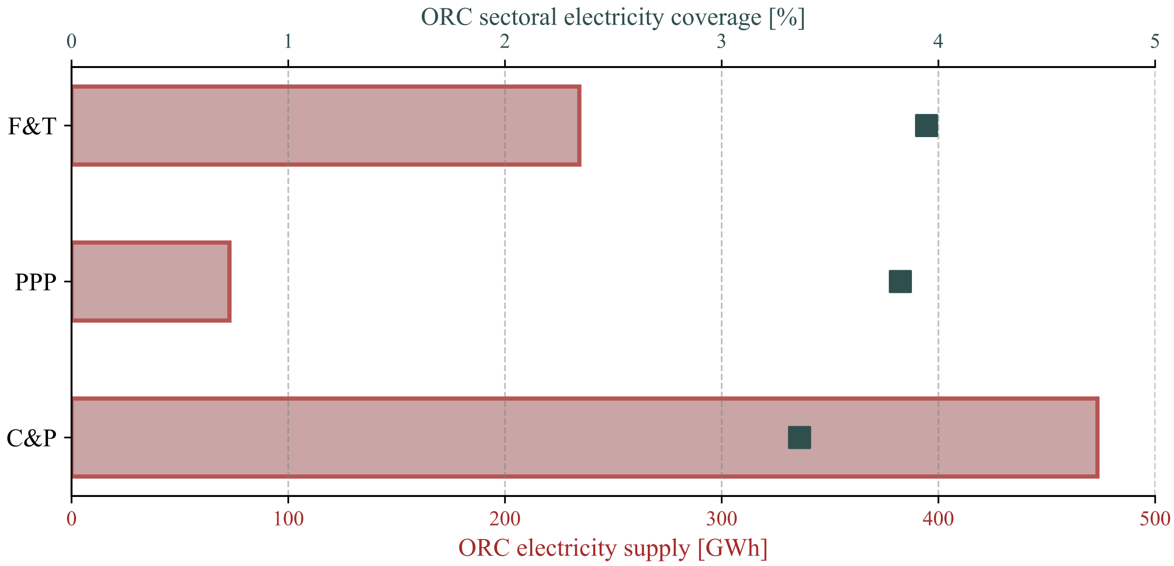


Figure 5.6 Sectoral ORC integration: net electricity supply and sectoral electricity consumption coverage.

Analyzing then the CO_2 emissions reductions induced by the integration of the ORC, Figure 5.7 shows that these reductions are relatively limited as well. They range from **10 Gt/year for the Paper sector**, to **33 Gt/year for the Food sectors** and up to **68 Gt/year for the Chemical sector**. Across the three sectors, this only represents a **1% reduction of the current sectoral**.

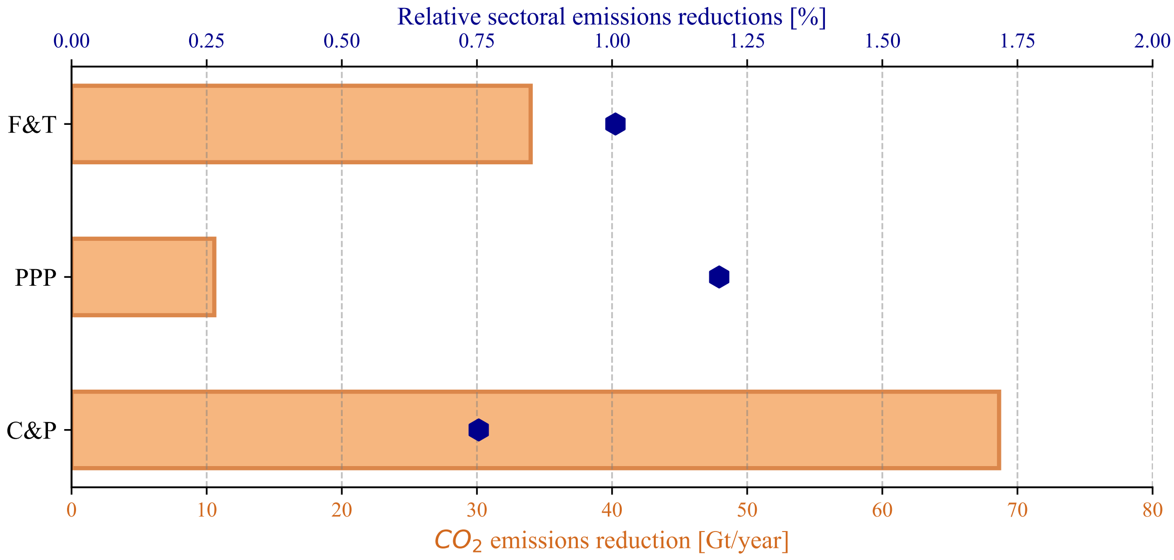


Figure 5.7 Sectoral ORC integration: net CO_2 emissions reductions and relative sectoral reductions.

These results demonstrate the limited potential of integrating ORC for low-grade waste heat recovery. Noting that the heat source temperature range for an ORC can reach up to 350°C [7], implementing this recovery technology should be prioritized for medium to high-temperature waste heat. One can think of the 360°C exhaust gases of the Cement production process encountered in the Non-Metallic Minerals sector, or the 200 to 300°C exhaust gases of oil and gas and burners, encountered in various sectors (Food & Tobacco, Paper, Wood and wood products, cfr. Chapter 3).

5.4 Carnot battery integration

The integration potential of the Carnot battery for industrial low-grade waste heat recovery shall now be explored. Starting with a thorough exposition of the selected methodology, including layout investigation, integration strategies, constraints, and evaluation criteria, this section proceeds to expose and analyze the resulting findings.

5.4.1 Methodology

Investigated layout

The investigated layout, depicted in Figure 5.8, corresponds to a Rankine-based Carnot battery. It is composed of a Vapour Compression Heat pump as the Heating Cycle and an Organic Rankine Cycle as the Heat engine. As for the Thermal Energy Storage, this analysis aims to compare the utilization and suitability of both Sensible and Latent storage: both configurations will be therefore considered.

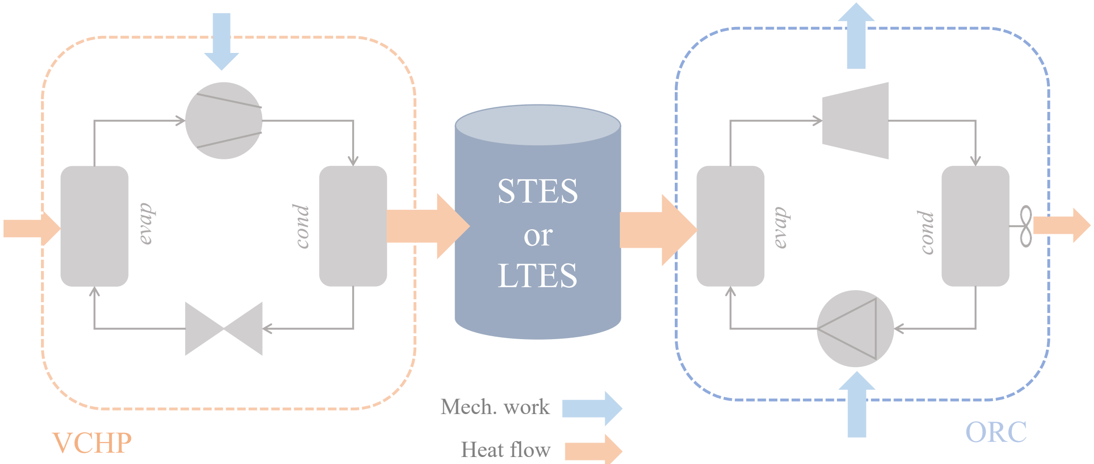


Figure 5.8 Investigated Carnot Battery layout

To describe the behavior of the overall system, three blocks are modeled sequentially, starting with the Vapour Compression Heat Pump. The following model (Equations

5.14 and 5.15) is used to describe this system, with the heat source being the waste heat (denoted as the colder side c) and the heat sink being the thermal energy storage (denoted as the hotter side h). Similarly to what was performed in Section 5.2.1, the objective is to determine the theoretical Coefficient of Performance (COP_{th}) of the heat pump using the Lorenz model, which considers the glide temperatures of both the heat pump's heat sink and heat source, and relate it to the actual performance of the machine through the second law factor η_{2nd}.

Vapour compression heat pump performance

$$COP_{th} = \frac{T_{h,HP,LM}}{T_{h,HP,LM} - T_{c,HP,LM}} \quad \text{with} \quad T_{LM} = \frac{T_{in} - T_{out}}{log\left(\frac{T_{in}}{T_{out}}\right)} \tag{5.14}$$

$$COP = \eta_{2nd,HP} COP_{th} \tag{5.15}$$

The Organic Rankine Cycle responds also to a similar model employed in Section 5.3, and is described by Equation 5.16 and 5.17. Once again, the objective was to express the actual efficiency of the machine with its theoretical value η_{th} corrected by a Second Law coefficient $\eta_{2nd,ORC}$.

Organic Rankine Cycle performance

$$\eta_{ORC,th} = \frac{T_{h,ORC,LM} - T_{l,ORC,LM}}{T_{h,ORC,LM}} \quad \text{with} \quad T_{LM} = \frac{T_{in} - T_{out}}{log\left(\frac{T_{in}}{T_{out}}\right)} \tag{5.16}$$

$$\eta_{ORC} = \eta_{Lorenz,ORC} \eta_{th,ORC} \tag{5.17}$$

Integration strategy

Several integration strategies are evaluated, each impacting the performance of the Carnot battery.
This analysis aims to explore four hot storage temperatures ($T_{st,h}$): 90°C, 100°C, 120°C, and 140°C. Once the temperature of the hot reservoir is set, the low-temperature reservoir ($T_{st,l}$) is established by selecting the storage temperature spread ($\Delta T_{st,sp}$), which is defined as the temperature difference between the two reservoirs.
As expressed previously, this analysis will examine the potential offered by both Sensible Thermal Heat Storage (STES) and Latent Thermal Heat Storage (LTES). For latent thermal heat storage, Phase Change Material (PCM) can be used as the thermal energy storage medium, resulting in a theoretically null storage spread [35]. In both cases, the storage efficiency η_{st} is set to 90% assuming optimal insulation [36].

Regarding storage duration, optimal integration of Carnot batteries is typically achieved through daily storage. Most studies indicate a storage duration of 6 to 8 hours ([37], [38], [39]). This analysis will adopt a storage duration of 6 hours, aligning with most of those findings.

The waste heat temperature glide $\Delta T_{WH,gl}$, as detailed in Section 5.1, was assumed to be 10K. As for the ambient temperature, it was assumed to be 15°C, with a related temperature glide $\Delta T_{amb,gl}$ set at 5K.

Regarding the second law efficiencies of the heat pump and the ORC, a combination of modeling, assumptions, and literature review was used. Arpagaus et al. [18] indicated that most heat pumps exhibit a second law factor $\eta_{2nd,HP}$ between 40% and 60% in conditions corresponding to the Sensible Storage configuration. Consequently, a value of 50% was chosen for this latter configuration. For latent thermal storage, numerical simulation of a heat pump, with no heat sink temperature spread, showed that $\eta_{2nd,HP}$ is closer to 30%. Regarding the ORC $\eta_{2nd,ORC}$, extensive research did not yield specific values, they were therefore assumed to be 50% for STES and 40%, slightly below, for LTES.

Those parameters are summarized in Table 5.7.

Parameter name	**Symbol**	**Latent TES**	**Sensible TES**	**Ref.**
Fixed parameters				
Storage period	P_{st}	6h	6h	[37], [38], [39]
Heat source glide	$\Delta T_{gl,src}$	10K	10K	[27]
Ambient temperature	T_{amb}	15°C	15°C	[A]
Heat sink glide	$\Delta T_{gl,sink}$	5K	5K	[A]
Heat pump second law efficiency	$\eta_{2nd,ORC}$	30%	50%	[18][S]
ORC second law efficiency	$\eta_{2nd,ORC}$	50%	40%	[A]
Storage efficiency	η_{st}	90%	90%	[36]
Design parameters				
Hot storage temperature	$T_{st,h}$	90-140°C	90-140°C	[18]
Storage temperature spread	$\Delta T_{st,sp}$	0K	10-40K	[18] [35]

Table 5.7 Summary of Carnot battery model parameters, with corresponding sources. A stands for Assumption, and S for Simulation.

Constraints

Several constraints can impact the feasibility of integrating a Carnot battery, one of them being the choice of the hot storage temperature $T_{st,h}$ depending on the waste heat temperature T_{WH}.

As outlined in Chapter 2, the range of waste heat temperatures considered spans from 50 to 100°C. Depending on the storage temperatures under consideration, the temperature of the cold reservoir could descend below that of the waste heat at the evaporator outlet. In such instances, the implementation of a Carnot battery for waste heat recovery is deemed unsuitable, since it can lead to a configuration where the Heat Pump contribution decreases greatly [27] [40], degenerating into a simple TES + ORC layout.

Figure 5.9 presents the temperature change of the heat source (waste heat), heat pump refrigerant as well as the storage medium (in case of Sensible Thermal Energy Storage).

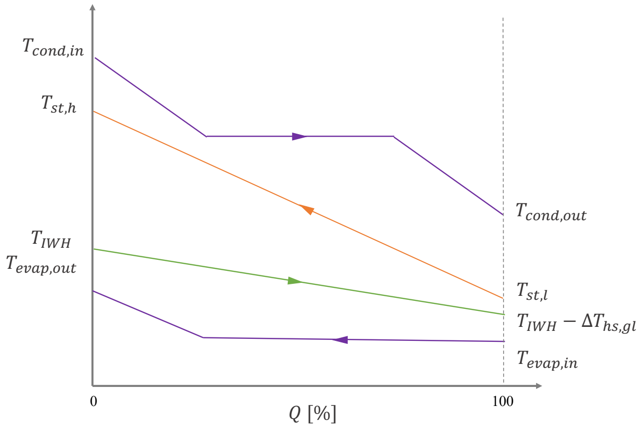


Figure 5.9 Heat transfer and temperature changes from the waste heat stream (green) to the heat pump working fluid (purple) and from the HP working fluid (purple) to the thermal storage medium (orange).

Potential evaluation

The objective was to evaluate the potential of various Carnot Battery integration strategies across the three sectors of interest, and their low-grade waste heat temperature ranges: 50-55°C, 80-85°C, and 100°C. For each case, the potential of the Carnot Battery is assessed using two performance indicators: the Power-to-Power efficiency (η_{p2p}) and the Carnot Second Law efficiency ($\eta_{II,C}$).

The **power-to-power efficiency** η_{p2p} is used to relate the heat pump electrical output $W_{net,HP}$ to the ORC electrical output $W_{net,ORC}$. It is influenced by the Coefficient of Performance COP of the Heat Pump, and the efficiencies of the storage unit η_{TES} and the Organic Rankine Cycle η_{ORC} (see Equation 5.18).

Power-to-power efficiency

$$\eta_{p2p} = \frac{W_{net,ORC}}{W_{net,HP}} = COP\eta_{ORC}\eta_{TES} \tag{5.18}$$

Maximizing η_{p2p} requires finding a balance between the Heat Pump's coefficient of performance COP and the ORC's efficiency η_{ORC}. Specifically, a lower lift enhances the heat pump's COP but results in a decreased high storage temperature, which negatively impacts the ORC efficiency, as depicted in Figure 5.10
In the case of TI-PTES, it is also necessary to express the quality of waste heat as part of the performance indicator. The exergy efficiency, η_{ex}, aims to account for both heat recovery and electricity storage efficiency, and is defined in [41] as follows (with Ex_{hs} denoting the exergy input of the heat source-the waste heat):

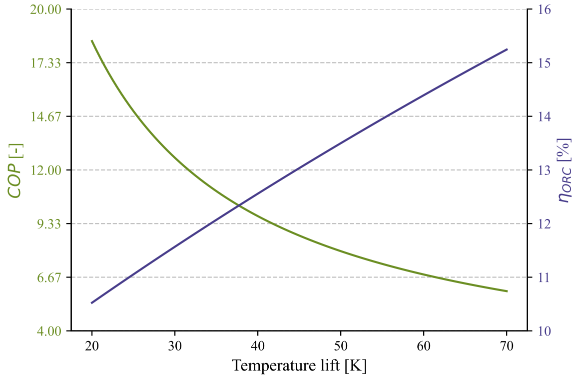


Figure 5.10 Parallel evolution of the heat pump *COP* and the ORC efficiency for different heat pump temperature lift. Waste heat was set to be 80°C to generate this figure.

$$\eta_{ex} = \frac{E_{el,out}}{E_{el,in} + Ex_{WH}} \quad \text{with} \quad Ex_{WH} = Q_{WH} m_{WH} c_{p,WH} T_{amb} ln\left(\frac{T_{WH,in}}{T_{amb}}\right) \tag{5.19}$$

Within the context of this analysis, the waste heat characterization conducted previously does not account for the nature of the waste heat stream, c_p is therefore left unknown. In relation to the Carnot potential of waste heat W^C_{WH} defined in Chapter 2, the **Second Law Carnot efficiency** $\eta_{II,C}$ was defined in this analysis to incorporate waste heat integration into the electrical energy storage efficiency. In Equation 5.20, $E_{e,in}$ and $E_{e,out}$ stand for the inlet and outlet electrical energy of the Carnot Battery, respectively retrieved at the VCHP compressor and ORC turbine.

Second law Carnot efficiency

$$\eta_{II,C} = \frac{E_{e,out}}{E_{e,in} + W^C_{WH}} \tag{5.20}$$

Maximizing $\eta_{II,C}$ amounts to maximizing electrical energy storage, which is prioritized in this analysis. Consequently, the focus is on maximizing the Carnot second law efficiency of the Carnot Battery rather than its Power-to-Power performance.

Once the electrical energy storage of the integrated Carnot Battery is established, the next step is to determine how to express its potential. This analysis focuses on its ability to meet electrical energy storage needs, particularly in an energy system with a higher penetration of renewables.

To do so, one can rely on the analysis of *Electricity storage needs for the energy transition in Belgium* conducted by Limpens et al. [42]. They defined four energy transition scenarios, summarized in Table 5.8, which vary in their energy mix. For each scenario, they determined the required electrical battery storage in GWh. The aim of this analysis is therefore to relate these storage requirements to the storage potential of the Carnot Batteries.

Scenario	**Description**	**Energy mix** [%]			CO_2	Electrical battery
		RE	**Nuclear**	**Gas**	[Mt/year]	storage needs [GWh]
Near-Future Society	Near-future society with a significant share of nuclear energy.	20	50	30	12.1	2.3
Mid-Term Transition	15-20 years away society with a balanced mix of renewable energy and gas.	50	10	40	16.2	8.9
High Renewable Share	Speculative case with a high share of renewable energy and no nuclear energy.	80	0	20	10.3	86.7
Full Renewable	Future society with 100% renewable electricity production.	100	0	0	4.6	241

Table 5.8 Description of the four energy mix transition scenarios considered, the associated carbon dioxide emissions, and the corresponding battery energy storage needs [42].

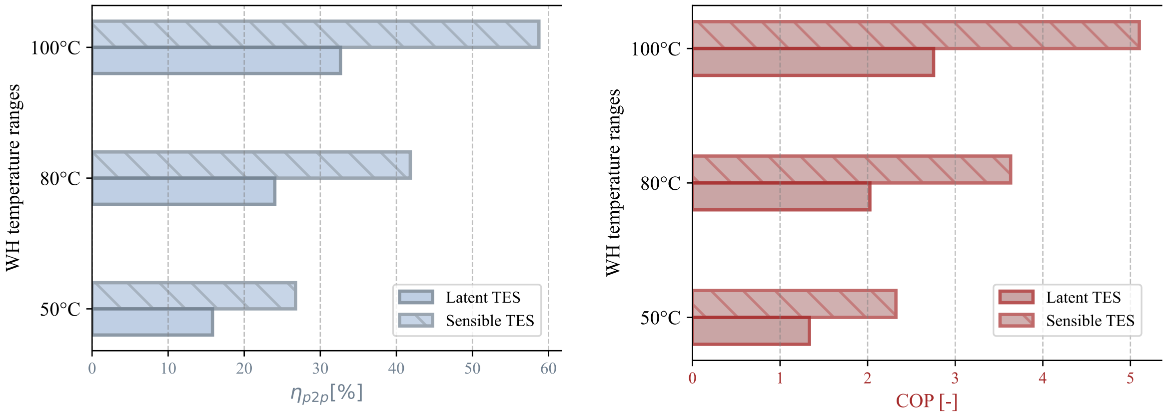
5.4.2 Results

Among the storage strategies considered (varying $T_{st,h}$ and $\Delta T_{st,sp}$), the focus was put on the ones maximizing the Second Law Carnot efficiency $\eta_{II,C}$. For both STES and LTES configurations, the optimal thermal energy storage temperature tends to be as high as possible: $T_{st,h}$ is therefore maintained at its maximum, and the storage spread is minimized.

Figures 5.11 depict the machine's performance across different waste heat temperature ranges.
Sensible TES exhibits superior performance compared to Latent TES in both Power-to-Power efficiency and Carnot Second Law efficiency. Power-to-power efficiency (η_{p2p}) tends to increase with higher heat source temperatures for both Sensible and Latent TES. Since the storage temperature is set (140°C in this analysis), higher waste heat temperatures will indeed reduce the heat pump lift, resulting in a higher COP and thus improving η_{p2p}.

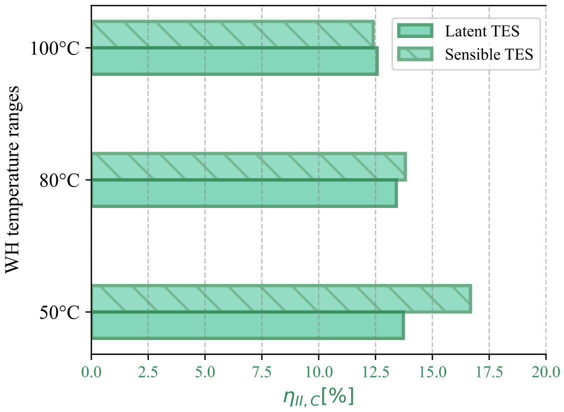
Regarding Carnot Second Law efficiency ($\eta_{II,C}$), the enhanced performance of Sensible TES is linked to its better matching of the heat source - the waste heat. However, the higher its temperature, the lower the difference between Latent and Sensible TES performances.

Overall, the lower COP of the LTES configuration leads to its higher potential to store electrical energy. This is visible on Figure 5.12, which depicts the electrical energy storage potential of Carnot Batteries, for the two Thermal Energy Storage configurations chosen (STES and LTES) and for the three sectors under consideration - Chemical and Petrochemical (C&P), Paper, pulp and print (PPP) and Food and Tobacco (F&T).



(a) Power-to-power efficiency

(b) COP of the heat pump



(c) Second law Carnot efficiency

Figure 5.11 Carnot Battery performance with regards to the TES type and the waste heat temperature range. These results were obtain with the storage strategies maximizing $\eta_{II,C}$: $T_{st,h}$ = 140°C and $\Delta T_{sp,st}$ = 10K for STES.

It can indeed be observed that Latent TES produces better results in terms of electricity storage potential. This figure also relates the potential of the thus-implemented Carnot Batteries to fulfill the electrical energy storage requirements of a fully decarbonized energy system (scenario D in Table 5.8).

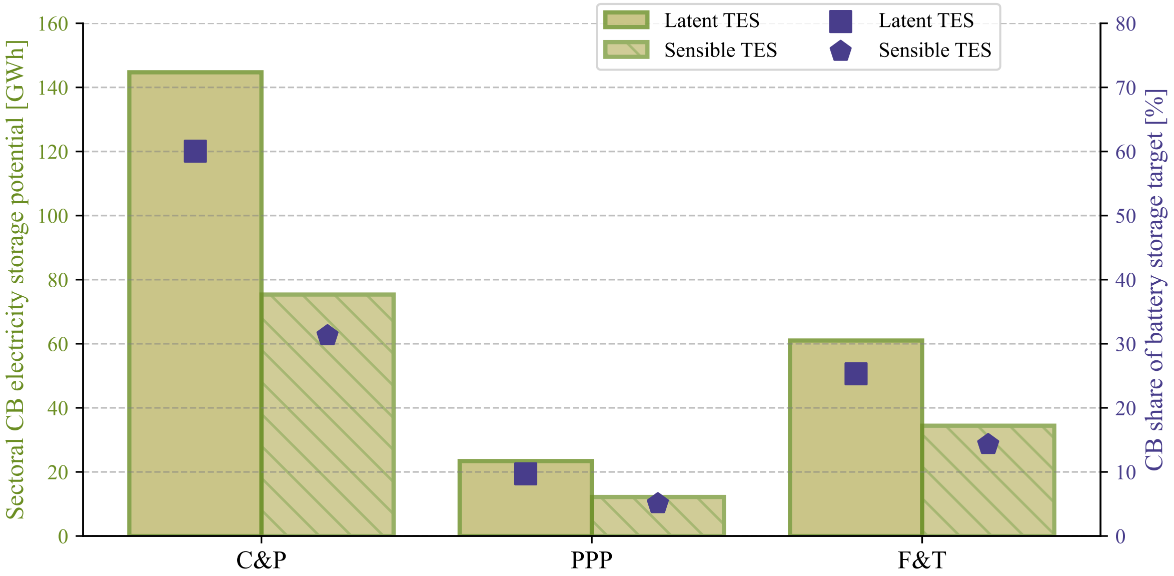


Figure 5.12 Sectoral electricity storage potential of Carnot batteries for sensible and latent TES. These sectoral storage potentials are correlated with their respective contributions to the battery storage target in a fully decarbonized Belgian energy system (scenario D see Table 5.8).

Tables 5.9 and 5.10 present the results concerning the share of Carnot Battery in the electricity storage target of batteries determined by the four decarbonization scenarios considered. Due to the escalating storage requirements associated with decarbonization, the potential of Carnot Batteries largely exceeds the electrical storage demand in scenarios A to C.

Overall, it is notable that, similarly to the Heat Pump integration analysis results, the Chemical and Petrochemical sector demonstrates the highest potential, followed by the Food and Tobacco, and the Paper sector.

Sector	CB [GWh]	CB storage coverage for scenario [%]			
		A	B	C	D
C&P	75.25	3276.05	846.62	86.91	**31.27**
PPP	12.18	529.35	136.80	14.04	**5.05**
F&T	34.42	1496.47	386.73	39.70	**14.28**
Total	121.94	5301.88	1370.15	140.65	**50.60**

Table 5.9 Carnot battery potential - **Sensible TES** - regarding the 4 scenarios of interest, scenario D representing a fully decarbonized Belgian energy system.

Sector	**CB [GWh]**	**CB storage coverage for scenario [%]**			
		A	B	C	**D**
C&P	144.71	6291.68	1625.94	166.91	**60.05**
PPP	23.38	1016.59	262.71	26.97	**9.71**
F&T	61.00	2652.12	685.38	70.36	**25.31**
Total	229.09	9960/38	2574.03	264.23	**95.06**

Table 5.10 Carnot battery potential - **Latent TES** - regarding the 4 scenarios of interest, scenario D representing a fully decarbonized Belgian energy system.

6

Conclusion

This analysis has explored the industrial waste heat potential in Belgium and evaluated three technologies for waste heat recovery: heat pumps, Organic Rankine Cycle (ORC), and Carnot Batteries. The findings reveal significant opportunities for energy optimization and emissions reduction across key industrial sectors. The following sections summarize the primary insights and actionable recommendations drawn from this study.

6.1 Industrial waste heat potential in Belgium

The initial part of the analysis focused on estimating and characterizing industrial waste heat in Belgium. Since 2005, it can be observed that the waste heat energy content slightly diminished (from 35 to 30 TWh), but its Carnot potential remains consistent, with more than **10 TWh of possible technical work**. Assuming a heat-to-power conversion efficiency of 50 %, this would lead to nearly 6 TWh of electricity, representing 15% of the annual electricity consumption of the Belgian industry.

It revealed that **45% of the total industrial waste heat energy content** occurs at **low temperatures, below 100°C**. On a national scale, the sectors with the highest Waste Heat Carnot Potential - the theoretical technical recoverable work - are the **Chemical and Petrochemical** sector (1 TWh), the **Food and Tobacco** sector (0.7 TWh), and the **Paper, Pulp, and Print** sector (0.3 TWh).

The analysis utilized a comprehensive database [1] that describes industrial processes, allowing for a detailed characterization of waste heat by process origin and temperature range. The findings indicated that low-temperature waste heat predominantly occurs as **effluents in cooling services**. Three distinct temperature ranges of these effluents were identified: **50-55°C** in electrical motors and burner effluents, **80-85°C** in compressor and natural gas engine effluents, and **100°C** in gasifier effluents, specific to the Chemical and Petrochemical sector.

6.2 Industrial Waste heat harvesting: recommendations

This analysis examined the potential of three technologies for industrial waste heat harvesting: heat pumps, Organic Rankine Cycle (ORC), and Carnot Battery integration. The following key observations and recommendations have emerged:

- The integration of heat pumps to harvest low-grade waste heat in the **Chemical & Petrochemical** sectors holds significant potential. This approach could meet **all its sectoral heat requirements below 200°C** and **30% of the overall heat requirements** of this sector. Regarding the **Food & Tobacco** sector, heat pump integration would cover **46.7% of the overall heat requirements**, as the large majority of these are below 200°C [29].
- Decarbonizing Belgian energy systems does not significantly enhance emission reductions from heat pump integration in the Chemical and Food sectors. Therefore, integrating heat pumps into the current energy systems is highly advisable, with no waiting for decarbonization. In the **Chemical sector**, this could result in a **26.7% reduction** in emissions (**-2.5** Mt $CO_{2,eq}$/year), and in the **Food and Tobacco sector**, a **23.5% reduction** (**-0.8** Mt $CO_{2,eq}$/year).
- In the **Paper sector**, the benefits of heat pump integration for low-grade waste heat recovery would **more than double** if electricity becomes **fully decarbonized**, increasing from a **12% reduction** in $CO_{2,eq}$ emissions (**-0.1** Mt $CO_{2,eq}$/year) to nearly **27%** (**-0.23** Mt $CO_{2,eq}$/year). Given the sector's current energy mix (predominantly renewable energies, electricity, and natural gas), the implementation of heat pumps is highly recommended in the case of a decrease in the electricity carbon footprint, and could cover **up to 40% of the overall sectoral heat requirements**.
- The **integration of Organic Rankine Cycle** for harvesting **low-grade industrial waste heat** in Belgium shows **limited impact** on sectoral electricity needs coverage (between 3% and 4% across sectors) and CO_2 emissions reductions (roughly 1% of respective sectoral emissions). ORC integration should be prioritized for **medium to high-temperature waste heat**, such as exhaust gases from oil and gas burners in sectors like Wood, Paper, Food, and Cement production. Further analysis would be advised to assess its full potential.
- As Belgium aims to transition to an energy system dominated by intermittent renewable energy sources, the need for electrical energy storage will increase significantly. In a fully decarbonized energy system, integrating Carnot Batteries

with Sensible Thermal Energy Storage in the Chemical, Paper, and Food sectors could cumulatively store **121 GWh of electrical energy annually**, covering **50% of the electrical battery storage needs**.

In summary, the integration of heat pumps and Carnot Batteries presents considerable opportunities for harnessing industrial waste heat in Belgium. In the context of low-temperature waste heat harvesting, the Waste heat Management Hierarchy presented in Chapter 4 can be updated as depicted in Figure 6.1. As always, the aim is first to reduce or reuse the identified losses occurring within a process. But when considering the harvesting of such low-grade waste heat, the priority should be put on its recovery through heat pumps, and Carnot Battery, especially in energy systems relying on intermittent renewable energy sources. Coming last and as explained previously, the integration of the Organic Rankine Cycle, as explained, showed limited potential in both industrial electricity needs coverage and emissions reductions.

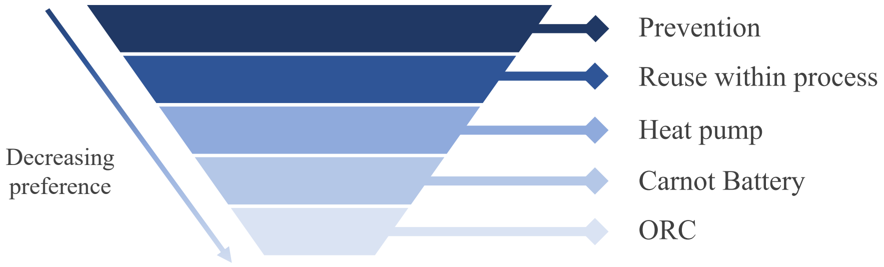


Figure 6.1 Management hierarchy of industrial low-grade waste heat recovery

Investment in research and development is crucial for advancing the efficiency and effectiveness of waste heat recovery systems, and strategic deployment initiatives are essential to ensure the widespread adoption of these technologies. This includes policy support, financial incentives, and collaboration between government, industry, and research institutions to overcome barriers to implementation and scale up successful initiatives. By prioritizing further research and strategic deployment efforts, Belgium can maximize the energy-saving potential of industrial waste heat recovery technologies, contributing significantly to its sustainability goals and environmental commitments.

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A

Appendix A: Industrial waste heat survey

Waste heat estimation in the Belgian industry - *Estimation de la chaleur fatale en industrie belge*

------------------ENGLISH VERSION------------------

UCLouvain **Master thesis** in Mechanical Engineering: "***Potential of Carnot Batteries in the recovery of waste heat generated by the Belgian industry below 100°C?*** ".

Waste heat refers to the **thermal energy produced as a byproduct of industrial processes**, often released into the environment unused. Recovering waste heat is crucial as it presents a valuable opportunity to **enhance energy efficiency**, **reduce environmental impact**, and **optimize resource utilization**.

Carnot Battery is an advanced **energy storage system** designed to store electrical power on the basis of a heat source, in this case waste heat.

Part of the research consists in **estimating waste heat in Belgium** through **data collection** in Belgian companies. We kindly request that you furnish details regarding the **generation of waste heat** stemming from a **pivotal process** within your company, such as energy consumption, efficiency, and related factors.

------------------VERSION FRANCAISE------------------

Mémoire de l'UCLouvain en Ingénierie Mécanique : "**Potentiel des batteries Carnot dans la récupération de la chaleur fatale générée par l'industrie belge en dessous de 100°C ?**".

La **chaleur fatale** fait référence à l'**énergie thermique** produite en tant que **sous-produit des processus industriels**, souvent rejetée dans l'environnement sans avoir été utilisée. La **récupération de la chaleur fatale** est cruciale car elle offre une opportunité d'**améliorer l'efficacité énergétique**, de **réduire l'impact environnemental** et d'optimiser l'utilisation des ressources.

La **batterie Carnot** est un système de **stockage d'énergie** conçu pour stocker l'énergie électrique à partir d'une source de chaleur, en l'occurrence la chaleur fatale.

Une partie de la recherche consiste à **estimer la chaleur fatale en Belgique** grâce à la **collecte de données** dans les entreprises belges.

Nous vous demandons de bien vouloir nous fournir des détails concernant la **production de chaleur fatale** résultant d'un **procédé essentiel** au sein de votre entreprise, tels que la consommation d'énergie, l'efficacité et les facteurs connexes".

* Indique une question obligatoire

SECTION 1 : Company ID - *Identité de l'entreprise*

1. Company name - *Nom de l'entreprise*

____

2. Branch/sector - *Branche/secteur*

Une seule réponse possible.

○ Iron & Steel - Sidérurgie
○ Chemical & Petrochemical - Chimie et Pétrochimie
○ Non Ferrous Metals - Métaux non ferreux
○ Non Metallic Minerals - Minéraux non métalliques
○ Transport Equipements - Equipements de transports
○ Machinery - Machinerie
○ Food & Tobacco - Alimentation et Tabac
○ Construction - Construction
○ Textile & Leather - Textile et Cuir
○ Mining & Quarrying - Industrie extractive
○ Paper, Pulp & Print - Papier, pâte à papier et imprimerie
○ Wood & Wood Products - Bois et Produits du bois
○ Non Specified - Non specifié

3. Contact person - *Personne de contact*

____

4. E-mail address - *Adresse électronique*

____

SECTION 2: Annual consumption - *Consommation annuelle*

The aim is to focus on a **specific and representative process**, its corresponding consumption and the related production of waste heat. The process has to occur in Belgium.

L'objectif est de se concentrer sur un ***processus spécifique et représentatif****, sur sa consommation en énergie et sa production de chaleur fatale. Le procédé doit se dérouler en Belgique.*

5. Name of the considered process *

   Nom du procédé considéré

   ____

6. Reference year - *Année de référence*

   ____

Fossil sources - Energies fossiles

(related to the considered process - *lié au procédé considéré)*

Fill in with the amount and the units if needed. If a precise value is not available, please specify a range.

Indiquez le quantité et les unités si nécessaire. Si une valeur précise n'est pas disponible, veuillez indiquer une fourchette.

7. Electricity [MWh/year] - *Electricité [MWh/an]*

   (produced with fossil sources - *produite avec des énergies fossiles)*

   ____

8. Natural gas [scm/year] - *Gaz naturel [scm/an]*

   ____

9. Carbon coke [tons/year] - *Coke de carbone [tonnes/an]*

10. Diesel [l/year] - *Diesel [l/an]*

11. Other - *Autre*

Please specify the type and units - *Veuillez préciser le type et les unités*

Renewable sources - *Energies renouvelables*

(related to the considered process - *lié au procédé considéré)*

Fill in with the amount and the units if needed. If a precise value is not available, please specify a range.

Indiquez le montant et les unités si nécessaire. Si une valeur précise n'est pas disponible, veuillez indiquer une fourchette.

12. Electricity [MWh/year] - *Electricité [MWh/an]*

13. Photovoltaic [MWh/year] - *Photovoltaïque [MWh/an]*

14. Wind Power [MWh/year] - *Energie éolienne [MWh/an]*

Biomass - *Biomasse*

15. Agricultural waste [tons/year] - *Déchets agricoles [tonnes/an]*

16. Forest residues [tons/year] - *Résidus forestiers [tonnes/an]*

17. By-products of the food industry [tons/year] - *Sous-produits de l'industrie alimentaire [tonnes/an]*

18. Specific energy crops [tons/year] - *Cultures énergétiques spécifiques [tonnes/an]*

19. Heat exchange (**sold)** [MWh/year] - ***Vente** de chaleur [MWh/an]*

20. Heat exchange (**bought)** [MWh/year] - ***Achat** de chaleur [MWh/an]*

21. Other - *Autre*

Please specify the type and units - *Spécifier le type et les unités*

22. Comments - *Commentaires*

____

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____

____

SECTION 3: Waste heat - *Chaleur fatale*

(related to the considered process - *lié au procédé considéré)*

23. Medium carrier of waste heat - *Vecteur de la chaleur fatale*

Une seule réponse possible.

○ Air/Fumes - Air/Fumées
○ Humid air - Air humide
○ Hot water - Eau chaude
○ Solid - Solide
○ Waste water/sludge - Eaux usées/boue
○ Autre : ______________________________

24. Process/system which generates waste heat - *Processus/système générant de la chaleur fatale*

Une seule réponse possible.

- ○ Burner, furnace, ovens, ... - Brûleur, four, ...
- ○ Process cooling system (water, oil, air) - Système de refroidissement du processus (eau, huile, air ...)
- ○ Process waste water - Eau usée de procédé
- ○ Chemical process - Procédé chimique
- ○ Compressor - Compresseur
- ○ Ventilator system - Système de ventilation
- ○ Cooling systems/Air conditioning - Systèmes de refroidissement/Air conditionné
- ○ Autre : ____________________

25. Yearly energy input of the process/system [MWh] - *Apport énergétique annuel du procédé/système [MWh]*

____

26. Efficiency of the process/system - Efficacité du procédé/système

____

27. If applicable, specify the installed power of the system [kW]

Si applicable, préciser la capacité installée du système [kW]

____

28. Flow of the exhaust gases/effluents [m3/h] - *Débit des gaz d'échappement/effluents [m3/h]*

____

29. Temperature [°C]

If a precise value is not available, please specify a range - *Si une valeur précise n'est pas disponible, veuillez spécifier une fourchette.*

____

30. Annual release profile [h/year] - *Profil des rejets annuels [h/an]*

____

31. Daily release profile - Profil des rejets journalier

Une seule réponse possible.

- ○ 24 [h/day]
- ○ 8 [h/day]
- ○ Autre : _______________

SECTION 4 : Additional information - *Informations additionnelles*

32. Describe the current waste heat recovery system if existing

Décrivez le système actuel de récupération de la chaleur fatale si existant.

____

____

____

____

____

33. Do you have any project or idea for recovering your waste heat?

Avez-vous un projet ou une idée pour récupérer la chaleur fatale ?

34. Are you willing to sell your waste heat to other company/investors?

Êtes-vous prêt à vendre votre chaleur fatale à d'autres entreprises/investisseurs ?

Une seule réponse possible.

○ Yes - Oui
○ No - Non

35. Have you received any proposals yet? - *Avez-vous déjà reçu des propositions ?*

Une seule réponse possible.

○ Yes - Oui
○ No - Non

36. Would you consider changing part of your energy source from a traditional one to waste heat?

Envisageriez-vous de remplacer une partie de votre source d'énergie traditionnelle par de la chaleur fatale ?

Une seule réponse possible.

○ Yes - Oui
○ No - Non

SECTION 5 : Data confidentiality - *Confidentialité des données*

37. Flag one or more. *

Plusieurs réponses possibles.

☐ All provided data can be made publicly available - Toutes les données fournies peuvent être mises à la disposition du public
☐ Only company name - Seulement le nom de l'entreprise
☐ Only waste heat medium - Seulement le vecteur de la chaleur fatale
☐ Only waste heat temperature - Seulement la temperature de chaleur fatales
☐ Only waste heat flow (and related properties) - Uniquement le flux de chaleur perdue* (et les propriétés associées)
☐ Only the e-mail and web site - Seulement l'adresse électronique et le site web
☐ No data can be made publicly available - Aucunes données ne peuvent être rendues accessibles

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